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Influence of corn seeding rate, soil attributes, and topographic characteristics on grain yield, yield components, and grain composition

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Influence of corn seeding rate, soil attributes, and topographic characteristics on grain yield, yield components, and grain composition

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DEDICATION

With gratitude this dissertation is dedicated to my wife, Melea, and two sons, William and Benjamin, who provided support, encouragement, relief, and perspective throughout this endeavor.

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ABSTRACT

Adoption of variable seeding rates has increased dramatically in recent years due to ability and feasibility of determining soil and topographic variability within fields. This research explores soil and topographic attribute interactions with seeding rate and the effect they have on corn yield, yield components, and grain composition. Experimental treatments included five seeding rates (61,750; 74,100; 86,450; 98,800; and 111,150 seeds ha^{-1}) in a randomized complete block design in three central Iowa fields from 2012 to 2014. Soil samples were analyzed for available P, exchangeable K, pH, soil organic matter, cation exchange capacity, and texture. Topographic data was determined with Light Detection and Ranging included elevation, slope, aspect, and curvature.

Seeding rate optimization resulted in seeding rate by attribute interactions: four site-years had a single seeding rate interaction (pH, in-field elevation, or curvature) and one site-year had three seeding rate interactions (pH, CEC, and SOM). When seeding rate optimization was performed, three site-years resulted in seeding rate responses warranting variable rate seeding.

When seeding rates increased, kernel rows ear^{-1}, kernel number ear^{-1}, and kernel weight decreased. Kernel number ear^{-1} was influenced by available P and pH, whereas kernel weight was influenced by available P, pH, slope, and in-field elevation. Zipper ears and plant barrenness were more prevalent as seeding rates increased and when rainfall was limiting. While seeding rate and individual soil and topographic attributes influenced yield components, interactions with seeding rate rarely influenced yield components.

Grain composition was not affected by seeding rate. Seeding rate interactions with soil and topographic attributes infrequently influenced grain composition. Grain yield always explained more of the variation in grain composition than the selected soil and topographic attributes. Available P, exchangeable K, and in-field elevation did influence individual grain composition parameters.

Corn seeding rate is an important determining factor for grain yield and yield components, however, it did not influence grain composition. Seeding rate along with its interactions with soil and topographic attributes may be used for explaining yield components on a field by field and year to year basis.

CHAPTER I

INTRODUCTION

Since the introduction of hybrid corn in the 1930s, the corn grain yield trend has been increasing in Iowa and across the U.S. Corn Belt. In Iowa, there has been an increase of corn plant densities of approximately 825 plants ha^{-1} $year^{-1}$ since 2000 (USDA-NASS, 2015). At the present time, corn seeding rate recommendations in Iowa are between 74,100 and 98,800 seeds ha^{-1} (Mueller and Sisson, 2013; Woli et al., 2014). While across the U.S. Corn Belt seeding rate recommendations range from 56,800 to 98,800 seeds ha^{-1} or more (Hoeft et al., 2000; Hall et al., 2009; Thomison, 2011; Van Roekel and Coulter, 2011; Nafziger, 2012; Barr et al., 2013; Lauer, 2015; Nielsen et al., 2015). Higher corn seeding rates tend to be supported under irrigation or locations with adequate rainfall. Corn production in the western, southern, and eastern Corn Belt states tend to be associated with lower seeding rates. Corn seeding rate is also influenced by productivity level where higher seeding rates are associated with higher productivity areas.

Corn grain yield and yield components are greatly influenced by plant densities. Corn grain yields respond to plant densities with a curvilinear or quadratic response if plant densities are increased to supra-optimum densities. At plant densities below the optimal plant density for maximum yield, additional plants offset kernel number $plant^{-1}$ reduction due to competition for water, sunlight, and nutrients (Duncan, 1984; Duvick, 1997). Above the optimum seeding rate for maximum yield, there are reductions in kernel number $plant^{-1}$, kernel weight, and greater occurrence of plant barrenness (Tetio-

Kagho and Gardner, 1988; Maddonni and Otegui, 2006). Additionally, grain composition is affected by plant density. Higher plant densities result in lower grain protein concentration (Stickler, 1964; Sander et al., 1987; Ahmadi et al., 1993) but increasing both seeding and nitrogen fertilizer rates results in higher grain protein concentrations (Zuber et al., 1954; Genter et al., 1956).

In addition to plant density, genetics and environmental conditions influence corn yield components and grain composition (Earle, 1977; Stroshine et al., 1986; Bullock et al., 1989; Duvick, 1997; Tollenaar and Wu, 1999; White and Johnson, 2003). Evidence is strong that as plant density increases kernel numbers ear^{-1}, kernel numbers plant^{-1}, and kernel weights decrease (Sangoi et al., 2002; Borrás et al., 2003; Hashemi et al., 2005; Maddonni and Otegui, 2006; Boomsma et al., 2009). Duvick and Cassman (1999) reported that as seeding rate increased, grain protein decreased and grain starch increased. This agrees with earlier findings from Genter et al. (1956) who found that grain protein decreased at higher seeding rates, however, the decrease in grain protein could be minimized with additional nitrogen fertilizer.

There is little knowledge as to how yield components and grain composition are affected by interactions of seeding rate with soil attributes or topographic characteristics. Plant density yield response curves are also influenced by field variability such as topography and soil physical and chemical properties. Shanahan et al. (2004) found that the optimal plant density increased from areas of low to high productivity within fields and that in-field elevation was influential. In-field elevation influences corn grain yields differently depending on the environmental conditions. Under dry conditions yield productivity suffered at higher in-field elevations with lower soil organic matter, higher slopes, and convex slopes, whereas, productivity in depressions was reduced under conditions with adequate to surplus rainfall (Kravchenko and Bullock, 2000; Kravchenko et al., 2003; Kaspar et al., 2004). The spatial variability of topography and soil attributes can be determined and when combined with precision agriculture technologies there is the potential to manage this variability.

The use of site-specific field information combined with technological advancements in equipment capabilities is the premise upon which precision agriculture is based. Precision agriculture approaches can be used to manage crop requirements and agronomic practices in a site-specific manner to account for spatial and temporal variability (Searcy, 1995; Rawlins, 1996; Mulla and Schepers, 1997; Bouma, 1999; Hoeft et al., 2000). Advances in precision agriculture began with global positioning systems, geographic information systems, grid soil sampling, variable fertilizer applications, and yield mapping (Mackay, 1997; Daberkow and McBride, 1999; Taylor and Whelan, 2010). The concept of variable rate technology has become reality due to advancements in planter and monitor capabilities combined with improved geographic information systems (Clark and McGuckin, 1996; Bullock et al., 1998; Nafziger, 2012). Additionally, advisors and services offering variable seeding rate approaches are now available from seed companies, retail agronomy outlets, and crop consultants.

The goal of this research was to characterize the spatial variability of soil properties, topographic characteristics, and corn yield productivity to make better site-specific seeding rate decisions while improving yield productivity and grain quality. The research objectives were to: 1) determine seeding rate interactions with soil attributes and topographic characteristics; 2) detect soil attributes and topographic characteristics to determine optimal seeding rates; 3) identify how seeding rate, soil attributes, and topographic characteristics affect yield components; and 4) determine the influence of seeding rate, soil attributes, and topographic characteristics on grain quality parameters such as grain protein, oil, and starch concentrations and grain density.

Dissertation Organization

This dissertation is organized in a journal manuscript format with five chapters. Chapter 1 is a general introduction. Chapter 2 is a journal manuscript that has been submitted to Precision Agriculture and identifies corn seeding rate optimization based on seeding rate interactions with soil parameters and topographic characteristics. Chapter 3 is a journal manuscript that will be submitted to Field Crops Research and examines the influence of corn seeding rate, soil parameters, and topographic characteristics on grain quality. Chapter 4 is a journal manuscript that will be submitted to Field Crops Research and identifies how yield components are influenced by corn seeding rate, soil parameters, and topographic characteristics. Chapter 5 is a general conclusion highlighting results from the three previous chapters.

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CHAPTER 2

SEEDING RATE OPTIMIZATION OF CORN (*ZEA MAYS* L.) IN IOWA, USA

A paper submitted to Precision Agriculture

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Abstract

Variable seeding rate capability has increased dramatically in recent years. Farmers and agronomists frequently collect and analyze soil samples to determine nutrient needs for subsequent crop production. The objective of this research was to optimize seeding rates to maximize yield using key soil and topographic parameters as factors. Experimental treatments included five corn seeding rates (61,750; 74,100; 86,450; 98,800; and 111,150 seeds ha^{-1}) in a randomized complete block design in three central Iowa fields from 2012 to 2014 (nine site-years). Soil samples were analyzed for available phosphorus (P; Olsen method), exchangeable potassium (K; ammonium-acetate method), pH, soil organic matter (SOM), cation exchange capacity (CEC), and texture. Topographic data (in-field elevation, slope, aspect, and curvature) were determined from publically available Light Detection and Ranging (LIDAR) data. In four site-years no interaction occurred between seeding rate and the descriptive variables. Three of the site-years resulted in a negative linear seeding rate response which made it impossible to determine an optimum seeding rate above the lowest seeding rate treatment. The seeding rate optimization process in five site-years resulted in seeding rate by variable interactions; four site-years had a single seeding rate by variable interaction (pH, in-field

elevation, or curvature) and one site-year had three seeding rate by variable interactions (pH, CEC, and SOM). This research was successful 56 percent of the time in determining an optimum seeding rate using soil and topographic parameters but inconsistent in determining a common descriptive variable that interacted with corn seeding rates for determination of an optimum seeding rate.

Introduction

It is common knowledge that the corn grain yields have increased since the 1930's in Iowa and across the U.S. Corn Belt. Corn plant densities have increased by roughly 825 plants hectare^{-1} year^{-1} in Iowa since 2000 (USDA-NASS 2015). As corn grain yield increased, plant densities have also increased with a correlation of 0.65 (USDA-NASS 2015). Currently, seeding rate recommendations that maximize yields for rainfed corn production in the central U.S. Corn Belt range from 69,000 to 98,800 seeds hectare^{-1} or more (Hoeft et al. 2000; Mueller and Sisson 2013; Nafziger 2012; Nielsen et al. 2015; Woli et al. 2014).

Corn grain yields respond to plant densities with a curvilinear response where an optimal plant density can be determined. Up to the optimal plant density, increasing plant densities increase grain yields more than the negative effect on per plant yield (Duncan 1984). After maximum yield is attained, competition for water, nutrients, and light become too great causing both field and per plant yields to decrease. Plant density yield response curves are influenced by biotic and abiotic factors (Shanahan et al. 2004; Van Roekel and Coulter 2011). Agronomists often assume that biotic yield-limiting factors occur in-season such as incidence and severity of insects, weeds, and pathogens and that these factors are minimized by management practices to as great an extent as possible in order to maximize yield. Abiotic factors that cause yield variability include topography as well as soil physical and chemical properties (Kaspar et al. 2004; Kravchenko and Bullock 2000; Kravchenko et al. 2003; Papiernik et al. 2005; Shanahan et al. 2004). The use of precision agriculture technologies has the potential capability to manage field variability associated with these abiotic factors.

Precision agriculture is based on the premise of using field information and advances in technology to manage crop requirements and agronomic practices in a site-specific manner to account for spatial and temporal variability (Bouma 1999; Hoeft et al. 2000; Mulla and Schepers 1997; Rawlins 1996; Searcy 1995). Early advances in precision agriculture included grid soil sampling, variable fertilizer applications, global positioning systems and yield mapping (Daberkow and McBride 1999; Mackay 1997; Taylor and Whelan 2010). Over the last two decades, variable rate seeding has developed from a concept to reality (Bullock et al. 1998; Clark and McGuckin 1996; Nafziger 2012). The advent of planter and monitor technology with the capability of planting at variable seeding rates across a field has given farmers and agronomists the ability to manage plant density using site-specific approaches to potentially increase productivity and profitability. Agronomists are now offering advice and services on variable rate seeding approaches.

Early in the adoption of variable rate seeding technology Bullock et al. (1998) stated that for variable seeding to be profitable and productive there needed to be a spatial relationship between yield and plant density as well as the influence of topographic and soil parameters on the relationship between grain yield and plant density. Therefore, these authors observed that variable rate seeding would not be feasible at that time because of the inability to feasibly characterize fields.

Initially site-specific, variable rate seeding determinations for corn were based on past yield productivity where higher yielding areas received higher seeding rates (Bullock et al. 1998; Butzen et al. 2012; Lowenberg-DeBoer 1999). However in Minnesota, Lamb et al. (1997) found that neither higher nor lower yielding field areas were consistent from year to year and that only 4 to 42 percent of grain yield variability in a given year was accounted for by grain yield from previous years.

As variable rate seeding technology becomes more widely available and other precision technology improves, variable rate seeding is now often based not only on past yield productivity but also soil fertility, soil texture, SOM, landscape position, in-field elevation or some combination thereof (Butzen et al. 2012; Doerge 1999; Gunzenhauser and Shanahan 2011). Many of these factors relate to corn yield variability. Previously in Iowa, Kaspar et al. (2003) determined that higher landscape positions and steep slopes had lower yield potential than lower landscape positions in years with below average rainfall. Conversely, depressions and slight hillslopes had lower yield potential than landscape positions conducive to topographic drainage in years with above normal rainfall. These findings confirmed earlier work by Spitze et al. (1973) showing grain yields in northeast Nebraska were influenced by soil drainage and topography and bottomland without drainage had higher yield potential than slopes and ridgetops.

The goal of this research was to 1) identify soil and topographic parameters that interact with seeding rate to influence corn grain yield and 2) determine potential soil and topographic parameters that can be used for site-specific optimization of corn seeding rates.

Methods

Experimental design

A field experiment was conducted over three growing seasons from 2012 to 2014 at three locations in central Iowa, USA to study corn response to seeding rate across landscapes. The fields were rainfed in the Clarion-Nicollet-Webster soil association (Clarion [fine-loamy, mixed, mesic, Typic Hapluduolls], Nicollet [fine-loamy, mixed, mesic, Aquic Hapluduolls], and Webster [fine-loam, mixed, mesic, Typic Endoaquolls]). The same three sites (Ames, 42°00’50.63”N, -093°44’24.81”W; Kelley, 41°57’09.27”N, -093°41’24.60”W; and Ogden, 42°00’21.55”N, -094°00’49.08”W) were used each of the three years of the experiment in a corn following corn rotation. Corn was also planted in 2011 at all three sites.

The experimental design at each site was a randomized complete block. The Ames and Kelley sites were replicated four times and the Ogden site was replicated five times. Experimental treatments consisted of five seeding rates (61,750, 74,100, 86,450, 98,800, and 111,150 kernels ha^{-1}) planted in plots 12.2m (Ames and Kelley) wide or 9.1m (Ogden) by field length in a 76.2cm row spacing. Field length was approximately 400m at Ames and Kelley and 720m at Ogden.

Field operations were conducted by Iowa State University farm operations staff (Ames and Kelley) or the private farm operator (Ogden) including fall and spring tillage, fertilizer applications, planting, herbicide applications and harvest. At all sites a disk ripper was used for primary fall tillage and a full width field cultivator (Ames and Kelley) or a rotary harrow (Ogden) for secondary spring tillage. Planting and harvesting equipment was consistent across years (Table 1). Fields at all sites followed typical herbicide and soil fertility programs for phosphorus (P), potassium (K) and pH for the area (Mallarino et al. 2013). A target nitrogen (N) application of 224 kg ha^{-1} was applied as a split application at Ames and Ogden and as single spring pre-plant application at Kelley. Different hybrids were planted each site-year resulting in the use of nine hybrids (Table 1). Climatic data was collected from Daymet Software version 2.0 (Thornton et al. 2015) for summation of monthly and growing season precipitation and accumulated growing degree days for each site-year and 30-year means for each site (Tables 2 and 3). Dayment software interpolates and extrapolates daily weather parameters using weather observations, digital elevation models, algorithms, and computer software to produce 1km by 1km surface grids.

Field data collection

Subplots were established within each replicated seeding rate treatment 30m apart. At Ames and Kelley there were 11 subplots per strip and at Ogden there were 23 subplots per strip. A subplot consisted of the center two rows of each strip by 5.3m long and was staked after planting. Subplots were located and marked using an Ashtech MobileMapper 100 with a GNSS antenna that connected to the Iowa Real-Time Network for real-time kinematic (RTK) global positioning at a 1-2cm horizontal accuracy from year to year. Soil samples were a composite of 14 soil cores taken to a depth of 15cm at the 8.1m^2 subplot level and were collected between planting and the fourth leaf stage

(Abendroth et al. 2011). Soil nutrient and texture analysis was conducted at Midwest Laboratories (Omaha, NE, USA) using standard laboratory procedures. Soil nutrient analysis included P, K, pH, SOM, cation exchange capacity (CEC) (Dahnke 1975; Kalra 1997; Kuo 1996; Sumner and Miller 1996). The sodium bicarbonate method was used for P (Olsen et al. 1954) and the ammonium-acetate method was used for K (Helmke and Sparks 1996). Available water holding capacity (AWC) was calculated using soil texture and SOM based on Saxton and Rawls (2006).

Grain yield and topographic spatial data

Farm operators of each site mechanically combine harvested the plot area with combines equipped with calibrated yield monitors and GPS receivers to attain site-specific corn grain yield and moisture. The harvest width was 9.1m at Ames and Kelley, where logistically, the center 9.1m of the 12.2m seeding rate plot was harvested and the remainder of the plot (four outside rows) was used for collection of ear samples. At Ogden, the harvest width was 9.1m and the entire plot width was harvested. Yield monitor data were processed using Ag Leader Technology SMS Basic (Ames, IA, USA) before exporting to ArcMap (ESRI 2014). ArcMap was used to determine yield and grain moisture at the subplot level by creating 6m or 4.6m buffers around the central point of the subplot followed by a spatial join of the yield information. The buffer distance was half the plot width resulting in yield information for each subplot being an average of approximately five to seven yield monitor data points.

Topographic data were generated using 0.61m contours from the LIDAR 3m Digital Elevation Model (DEM) of Boone and Story counties (IA, USA) available from the Natural Resources Geographic Information Systems Library of the Iowa Department of Natural Resources (https://programs.iowadnr.gov/nrgislibx/). ArcMap spatial analyst tools were used to determine in-field elevation, slope, curvature, and aspect of each subplot. In ArcMap in addition to slope curvature, planar curvature (curvature perpendicular to the slope) and profile curvature (curvature parallel to the slope) can be determined (ESRI 2014). Positive curvature values result from convex slopes and negative curvature values result from concave slopes. Slope aspect identifies the direction a slope faces (0 to 360 degrees). For this analysis slope aspect was transformed to 'northness' with values of –1 to 1 where slope aspects of negative one are more south facing and slopes of positive one are more north facing.

Statistical analysis

Correlation and multiple regression analyses were conducted to understand and identify the key independent variables that best explained corn grain yield (SAS Institute 2012). A stepwise regression procedure was used with $\alpha = 0.05$ for variable addition and deletion in the final model prediction. Independent variable collinearity in the regression model was identified using variance inflation factors (VIF). Where VIF of greater than 10.0 was identified, related independent variables were removed from the regression analysis. Collinearity existed between planar and profile curvature which resulted in the use of combined slope curvature. Silt and AWC were removed because collinearity existed between sand, silt, clay, SOM, and AWC. Even with exclusion of independent variables due to VIF greater than 10.0, P, K, SOM, and CEC had a VIF > 10.0 in one, two, four, and two site-years respectively. These variables were important and are common parameters used by farmers and agronomists and therefore retained within the regression and mixed model analysis.

The optimum seeding rate optimization was estimated using a model where corn grain yield was the response variable. The initial model, included the effects of replication, seeding rate, seeding rate squared, identified soil and topographic parameters plus the seeding rate interaction with the soil and topographic parameters. A reduced model was then fit by excluding non-significant seeding rate interactions with soil and topographic variables. We considered whether to include spatial dependence among residuals by fitting models with spatially correlated residuals. Gaussian and Exponential covariance structures in which the correlation between each pair of subplots depended on their Euclidean distance which was computed from the X, Y coordinates of each subplot. None of the nine site-years showed evidence of spatial dependence in the residuals because the soil and topographic independent variables included in the mixed model accounted for the geographic dependence of the subplots.

Optimum seeding rates (SR_{opt}) at each subplot were determined by solving the model for maximum seeding rate:

$$Yield = \beta_0 + \beta_1 SR + \beta_2 SR^2 + \beta_3 (var \times SR) \tag{1}$$

$$Yield = \beta_0 + (\beta_1 + \beta_3 var) SR + \beta_2 SR^2 \tag{2}$$

SR_{max} solves the equation

$$\frac{dYield}{dSR} = \beta_1 + \beta_3 var + 2\beta_2 SR_{max} = 0 \tag{3}$$

$$SR_{opt} = SR_{max} = \frac{-(\beta_1 + \beta_3 var)}{2\beta_2} \tag{4}$$

where Yield is the corn grain yield, SR is the seeding rate, var is soil attributes or topographic characteristics that interact with seeding rate, SR_{max} is the seeding rate at which the highest yield can be expected, SR_{opt} is the optimum seeding rate for the subplot based on the derivatives of corn grain yield, seeding rate, and significant seeding rate × variable interactions. The PROC MIXED procedure was used for the optimum seeding rate computations.

Results and discussion

Field variability assessment

Descriptive statistics exposed the amount of variability in soil properties and topographic characteristics across and within sites with coefficient of variation (CV) values generally greater than 15% (Table 4 and 5; Fig. 1). This amount of variability was desired for the purpose of the experiment and sites were selected based on perceived and known variability.

Average corn grain yields across site-years were highly variable ranging from 10.4 to 12.7 Mg ha^{-1} with CV values ranging from 5.3% to 33.2% (Table 4; Fig. 2). The greatest within site-year corn yield variability was at Ames in 2013 which can be attributed to large variation in topographic characteristics combined with greater than normal precipitation following planting causing reductions in stand establishment in field depressions (results not shown). While Kelley in 2013 had low corn grain yield variability, it too experienced greater than normal precipitation in April and May which resulted in a mid-June planting date. Therefore, this site had less stand reduction due to saturated soil conditions than the other sites in 2013.

For all three sites, mean corn grain yields were the highest in 2012 and the lowest in 2013 (Table 4). Kelley was the lower yielding site and Ogden was the higher yielding site. The yearly corn yield variability can be attributed to climatic conditions: 2012 was extremely dry; 2013 was cool and wet in April and May, followed by dry conditions; and 2014 was cool and wet throughout the growing season (Tables 2 and 3). An additional factor that needs to be acknowledged is that site-year variability from climatic factors is also confounded by hybrid characteristics since a different hybrid was used for each of the nine site-years. This is supported by Shanahan et al. (2004) who found that corn population density response curves were similar in shape but influenced differently by hybrid and productivity management zones.

Correlation and regression analysis

Seeding rates and corn grain yield were correlated in seven of nine site-years. In six of these seven site-years, corn grain yields were negatively correlated with seeding rate (Table 6). Soil fertility parameters were inconsistently correlated with corn grain yields across site-years. In the abnormally dry year of 2012, slope, curvature and in-field elevation were negatively correlated with corn yield. Additionally, SOM and clay content were positively correlated with grain yield. In totality, the combination of these parameters suggest that water availability and storage are important parameters in determining yield potential and an optimal seeding rate for specific areas within fields, especially in years with dry weather conditions. Conversely, in 2013 and 2014, curvature and in-field elevation each were positively correlated with corn grain yield while clay and sand content were not consistently correlated with grain yield. Positive grain yield correlation with slope, curvature, and in-field elevation indicate that while the ability to capture and store water in a dry year is beneficial, in wet years a more variable topography results in water dispersion from the summit and hillslope landscape positions and higher corn yields. The influence of soil water drainage and storage on grain yields have been well known but are highly inconsistent depending on soil type, topography, and climatic conditions of the research sites (Kaspar et al. 2004; Kravchenko and Bullock 2000; Runge and Hons 1999; Spitze et al. 1973).

Generally, the step-wise regression models reflect the correlation coefficients for each site-year. The highest coefficients of determination (R^2) for the regression model analysis were at the Ames site with an R^2 of 0.65 and 0.77 in 2012 and 2014 respectively. The lowest R^2 values were at Kelley in 2013, Ogden in 2012, and Ames in 2013, R^2 = 0.16, 0.17, and 0.20 respectively. Regression analysis included seeding rate and/or seeding rate squared in all site-years except Ames in 2013. Most of the time the seeding rate and seeding rate squared parameters were negative and extremely low, indicating little influence of seeding rate on the yield prediction.

In both, Ames and Kelley the regression model R^2 values were much lower in 2013 compared to 2012 and 2014. These lower R^2 values can be attributed to areas of the field that had reduced plant densities and yield due to saturated soil conditions early in the year and dry conditions that were detrimental to grain production during grain fill later in the season. Therefore, most of the parameter coefficients in the regression model were low and therefore had little effect on the yield prediction.

Seeding rate optimization

Seeding rate optimization is a way to use known field characteristics combined with seeding rate treatments and yield outcomes to determine variable seeding rates for future plantings based on those known field characteristics. The seeding rate optimization analysis in four site-years, Ames 2013 and Kelley 2012, 2013, and 2014, did not result in an optimized seeding rate due to a lack of a seeding rate interactions with soil parameters and topographic characteristics (Fig. 4). This does not mean soil parameters or topographic characteristics do not influence corn grain yields. It does mean that the optimization of seeding rates was not affected by the selected field characteristics.

Five site-years had a seeding rate interaction with a soil parameter(s) and/or topographic characteristic(s). Of the five site-years, Ames 2014 had optimum seeding rates below the range of corn seeding rate treatments used in the experiment, thus limiting the validity and usefulness of the seeding rate optimization analysis for this site-year. This is very likely due to low coefficient estimates for seeding rate interactions with pH, CEC, and SOM combined with essentially no coefficient estimate for seeding rate squared ($-2.84e^{-10}$).

Four site-years (Ames 2012 and Ogden 2012, 2013, 2014) provided corn seeding rate optimizations that fell within the range of seeding rate treatments used in the experiment, three of which provided a range of optimum seeding rates large enough to develop a dynamic seeding rate response curve (Fig. 5). The Ames 2012 optimum seeding rates ranged from 92,950 to 95,430 seeds ha^{-1} while the Ogden site had mean optimum seeding rates of 83,270, 90,680, and 81,020 seeds ha^{-1} in 2012, 2013, and 2014, respectively. The Ogden site-year seeding rate response curves generally match up to seeding rate response curves used as the basis for corn seeding rate recommendations that maximize yields (Hoeft et al. 2000; Mueller and Sisson 2013; Nafziger 2012; Nielsen et al. 2015; Woli et al. 2014).

Conclusions

The site years of this study proved not only to have large variable of soil and topographic parameters but also considerable corn grain yield and optimum seeding rate variability. Individual sites exhibited different corn yield and seeding rate responses due in part to differences in field variability. Slope, curvature, in-field elevation, and SOM seemed to consistently be correlated with corn yield in dry climatic conditions of 2012. When the planting and growing season had normal to cool/wet conditions corn yield correlations to variables were less consistent. Regression models for all site-years were inconsistent in the amount of yield variability accounted for by the soil and topographic variables (16% to 77%).

When seeding rate optimization was performed, only three of nine site-years resulted in meaningful seeding rate response curves that warranted use of variable seeding rates across fields. Even in those site-years, there was considerable variation of the optimization model. These findings support the notion that for variable rate seeding to be viable there is a need for seeding rate to be influenced by soil attributes and topographic characteristics (Bullock et al. 1998) but an additional need is for consistency of seeding rate interaction with soil attributes and topographic characteristics from year to year and field to field.

Determining a single optimum seeding rate methodology based on soil and/or topographic variables across a farming operation seems unlikely due to seeding rate response and interactions with variability of climatic conditions and field characteristics. Based on this study, further research needs to be conducted to better understand how seeding rate optimization can be accomplished effectively. Development of seeding rate response curves for individual management zones based on indices that can account for the influence of soil fertility, water holding capacity, and landscape position on seeding rate response curves would be of great value.

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Table 1 Hybrid, planting date, planter model, harvest date and combine model at three central Iowa, USA field experiment sites from 2012 to 2014.

	Ames 42°00’50.63”N, -093°44’24.81”W			Kelley 41°57’09.27”N, -093°41’24.60”W			Ogden 42°00’21.55”N, -094°00’49.08”W		
Parameter	2012	2013	2014	2012	2013	2014	2012	2013	2014
Hybrid	Pioneer P0528XR	Pioneer 1161XR	Pioneer P1023AM	Channel 209-85VT3Pro	Pioneer 9910XR	Pioneer 34F07	Pioneer 1151HR	Pioneer P0993HR	Pioneer 1360CHR
Planting Date	11 May	18 May	7 May	14 May	14 June	9 May	9 May	14 May	7 May
Planter	John Deere 7000 with MaxEmerge row units			John Deere 7000 with MaxEmerge row units			John Deere DB60 with MaxEmerge II row units		
Harvest Date	28 Sept	16 Oct	20 Oct	2 Oct	28 Oct	30 Oct	20 Sept	7 Oct	11 Nov
Combine	John Deere 9550			John Deere 9550			John Deere 9870		

Table 2 Monthly and total growing season precipitation at three central Iowa, USA field experiment sites from 2012 to 2014 and the 30-year average precipitation. Precipitation was collected from Daymet Software version 2.0 (Thornton et al. 2015).

	Ames				Kelley				Ogden			
Month	2012	2013	2014	30-yr[a]	2012	2013	2014	30-yr	2012	2013	2014	30-yr
	mm											
April	134	159	176	103	130	162	180	104	123	159	115	99
May	71	267	143	127	73	279	140	131	70	258	132	124
June	82	95	266	139	81	96	265	140	81	107	233	137
July	53	40	91	119	49	40	83	117	30	25	97	114
August	84	32	182	128	87	30	193	128	69	25	162	120
September	59	50	133	84	57	53	135	84	55	40	133	82
Growing Season[b]	483	643	991	700	477	660	996	704	428	614	872	676

[a] 30-year; average monthly precipitation and average growing season accumulation from 1985 to 2014.
[b] 1 April to 30 September.

Table 3 Monthly and total growing season accumulated growing degree days (10^{o}C – 30^{o}C) at three central Iowa, USA field experiment sites from 2012 to 2014 and the 30-year average growing degree days. Precipitation was collected from Daymet Software version 2.0 (Thornton et al. 2015).

	Ames				Kelley				Ogden			
Month	2012	2013	2014	30-yr[a]	2012	2013	2014	30-yr	2012	2013	2014	30-yr
April	128	66	97	104	129	67	99	106	132	65	100	106
May	272	195	218	212	276	197	220	214	271	193	219	213
June	344	317	333	328	346	320	335	329	344	317	333	328
July	452	376	317	394	454	379	323	397	451	375	318	395
August	348	371	366	362	349	375	370	364	348	370	365	362
September	250	291	220	246	252	294	223	248	249	294	222	247
Growing Season[b]	1793	1615	1551	1647	1807	1633	1569	1658	1796	1613	1556	1651

[a] 30-year; average monthly precipitation and average growing season accumulation from 1985 to 2014.
[b] 1 April to 30 September.

Table 4 Grain yield and descriptive statistics of selected soil nutrient parameters at three central Iowa, USA field experiment sites from 2012 to 2014.

		Ames			Kelley			Ogden		
Parameter[a]	Year	Mean	Range	CV (%)	Mean	Range	CV (%)	Mean	Range	CV (%)
Grain Yield,	2012	12.2	4.8–15.4	12.6	11.3	5.8–13.7	11.8	12.7	5.1–16.2	13.9
Mg ha^{-1}	2013	10.4	0.4–13.3	33.2	10.7	6.4–12.3	8.8	10.8	0.9–16.0	17.4
	2014	11.6	5.6–14.1	12.0	11.0	2.1–13.8	20.7	12.3	10.4–14.4	5.3
P, mg kg^{-1}	2012	11	6–18	23.4	23	11–86	52.6	15	5–72	55.7
	2013	12	5–47	47.1	28	9–74	42.4	17	5–81	58.8
	2014	14	4–66	50.1	26	9 –61	37.4	19	5–68	50.4
K, mg kg^{-1}	2012	170	120–224	15.9	224	176–412	18.9	185	93–369	29.4
	2013	173	108–292	20.3	233	124–389	22.5	211	114–509	25.2
	2014	166	85–281	18.9	216	128–381	20.6	196	85–470	29.8
pH	2012	6.5	5.3–7.9	12.5	5.9	5.2–7.2	7.7	7.0	4.6–8.1	12.6
	2013	6.2	4.7–8.1	17.0	5.9	4.5–7.9	14.0	6.8	4.6–8.1	14.7
	2014	6.2	4.6–8.1	17.5	5.9	4.7–8	14.5	6.7	4.5–8.1	15.6
CEC,	2012	23.1	12.2–37.6	31.5	24.9	15.8–33.3	15.2	26.9	17.1–42.7	20.3
cmol kg^{-1}	2013	24.2	13.2–35.5	25.6	24.9	14.3–35.6	19.1	27.7	14.9–38.2	18.3
	2014	25.6	12.3–41.5	27.1	26.2	13.8–38.7	21.0	26.6	13.2–43.1	21.6
OM, g kg^{-1}	2012	40	14–68	36.5	34.5	22–57	18.0	42	24–86	27.6
	2013	39	11–69	39.6	32.7	13–64	25.7	44	21–86	24.6
	2014	45	15–78	35.8	38.7	18–65	21.8	47	22–95	24.3

[a] P, phosphorus; K, potassium; CEC, cation exchange capacity; OM, organic matter.

Table 5 Descriptive statistics of selected soil and topographic parameters at three central Iowa, USA field experiment sites.

	Ames			Kelley			Ogden		
Parameter	Mean	Range	CV (%)	Mean	Range	CV (%)	Mean	Range	CV (%)
Sand, $g\ kg^{-1}$	456	220–620	16.0	482	300–620	11.7	425	200–620	15.9
Clay, $g\ kg^{-1}$	223	160–340	16.2	215	120–320	15.7	235	80–500	21.2
Slope, degrees	8.5	0.3–31.3	67.5	6.7	0.4–21.7	61.6	5.2	0.1–15.9	60.0
Curvature[a]	–0.02	–5.09–3.42	–4643.1	0.06	–1.10–1.57	732.9	–0.04	–3.39–2.47	–1304.1
Aspect[b]	0.32	–1.00–1.00	191.5	–0.10	–1.00–1.00	–754.4	0.03	–1.0–1.0	2155.5
Elevation, m[c]	323	320–328	0.5	314	313–316	0.2	332	330 – 334	0.3

[a] Slope curvatures are convex when positive and concave when negative.
[b] Aspect transformed to ‘northness’ where 1 equals north facing slopes and –1 equals south facing slopes.
[c] Above sea level.

Table 6 Significant Pearson correlation coefficients of corn grain yield to soil and topographic parameters, 2012 to 2014.

	Ames			Kelley			Ogden		
	2012	2013	2014	2012	2013	2014	2012	2013	2014
Seeding rate	0.17**	ns	–0.55***	–0.38***	–0.27***	–0.15*	–0.10*	ns	–0.16***
P	0.55***	ns	–0.22**	0.27**	ns	–0.34***	0.15**	ns	0.43***
K	0.63***	ns	ns	0.30***	ns	–0.29***	ns	–0.26***	0.31***
pH	ns	–0.29***	–0.70***	ns	ns	–0.44***	0.09*	–0.26***	–0.40***
SOM	0.46***	–0.29***	–0.50***	0.36***	ns	–0.42***	0.19***	–0.37***	0.09*
CEC	0.43***	–0.33***	–0.42***	0.40***	ns	–0.33***	0.10*	–0.27***	ns
Sand	–0.52***	0.13*	ns	ns	ns	ns	–0.19***	ns	ns
Silt	0.46***	ns	–0.14*	ns	ns	ns	0.19***	–0.11**	ns
Clay	0.22**	ns	0.16*	ns	ns	ns	0.09*	ns	ns
Slope	–0.46***	0.24**	0.27***	–0.20**	ns	0.18**	–0.19***	0.28***	–0.09*
Curvature	–0.19**	ns	ns	–0.34***	ns	0.44***	–0.14**	ns	ns
Aspect	ns	ns	–0.29***	0.16*	ns	ns	–0.16**	0.11**	–0.14**
Elevation	–0.58***	0.24**	0.39***	–0.24**	ns	0.44***	–0.31***	0.53***	ns

Minimum and maximum number of observations for the correlation parameters: Ames-2012, n=187-220; Kelley-2012, n=180-220; Ogden-2012, n=352-554; Ames-2013, n=193-220; Kelley-2013, n=220; Ogden-2013, n=553-554; Ames-2014, n=219-220; Kelley-2014, n=220; Ogden-2014, n=552-554.
*, Significant at the 0.05 probability level; **, Significant at the 0.01 probability level; ***, Significant at the 0.001 probability level; ns, not significant.

Table 7 Regression models for predicting corn grain yields using seeding rate (rate and rate squared), soil parameters, and topographic characteristics. All models were significant at the 0.0001 probability level.

Site-year	Regression Model[a]	Model R^2
Ames, 2012	$Y = 135.76 + 1.35e^{-5}Rate – 8.69e^{-10}Rate^2 + 0.05K + 0.15pH – 0.02SOM – 0.14CEC – 6.06e^{-3}SD – 0.02CL – 0.07SL – 0.37E$	0.65
Ames, 2013	$Y = 19.76 + 0.01K – 0.35pH – 0.17CEC – 0.01SD – 0.01CL – 0.05SL – 0.25C$	0.20
Ames, 2014	$Y = 17.54 – 3.90e^{-5}Rate – 4.02e^{-10}Rate^2 - 0.01P + .01K – 0.77pH + 0.01SOM – 0.07CEC – 9.45e^{-4}SD – 0.02SL$	0.77
Kelley, 2012	$Y = 93.73 – 2.93e^{-5}Rate – 0.03P + 0.01K – 0.68pH + 0.16CEC – 8.86e^{-3}CL + 0.05SL – 0.34C + 0.49A – 0.27E$	0.50
Kelley, 2013	$Y = 85.04 – 1.37e^{-5}Rate – 2.37e^{-10}Rate^2 – 0.01P + 2.34e^{-3}K – 0.24pH + 0.03CEC – 2.54e^{-3}CL + 0.04SL – 0.23E$	0.16
Kelley, 2014	$Y = -193.34 – 2.07e^{-5}Rate – 0.01K – 0.90pH + 0.06CEC – 0.01SD – 0.01CL + 1.60C – 0.28A + 0.68E$	0.41
Ogden, 2012	$Y = 186.85 – 8.87e^{-6}Rate – 7.95e^{-10}Rate^2 + 0.03P – 7.76e^{-3}K – 5.66e^{-3}SD – 0.06SL – 0.33C – 0.26A – 0.51E$	0.19
Ogden, 2013	$Y = -333.64 – 4.32e^{-10}Rate^2 + 0.01P – 4.91e^{-3}K + 1.56e^{-3}SD + 4.64e^{-3}CL + 0.06SL – 0.19C + 1.03E$	0.32
Ogden, 2014	$Y = 69.85 – 6.21e^{-6}Rate – 6.23e^{-10}Rate^2 + 0.02P – 0.30pH + 0.01CEC – 0.02SL + 0.07C – 0.08A – 0.17E$	0.39

[a] Regression models derived from each site-year data set; Y = corn grain yield (Mg ha^{-1}); Rate = seeding rate (seeds ha^{-1}); P = phosphorus (mg kg^{-1}); K = potassium (mg kg^{-1}); SOM = soil organic matter (g kg^{-1}); CEC = cation exchange capacity (cmol kg^{-1}); SD = sand (g kg^{-1}); CL = clay (g kg^{-1}); SL = slope (degrees); C = curvature; A = aspect (radians); E = elevation (m).

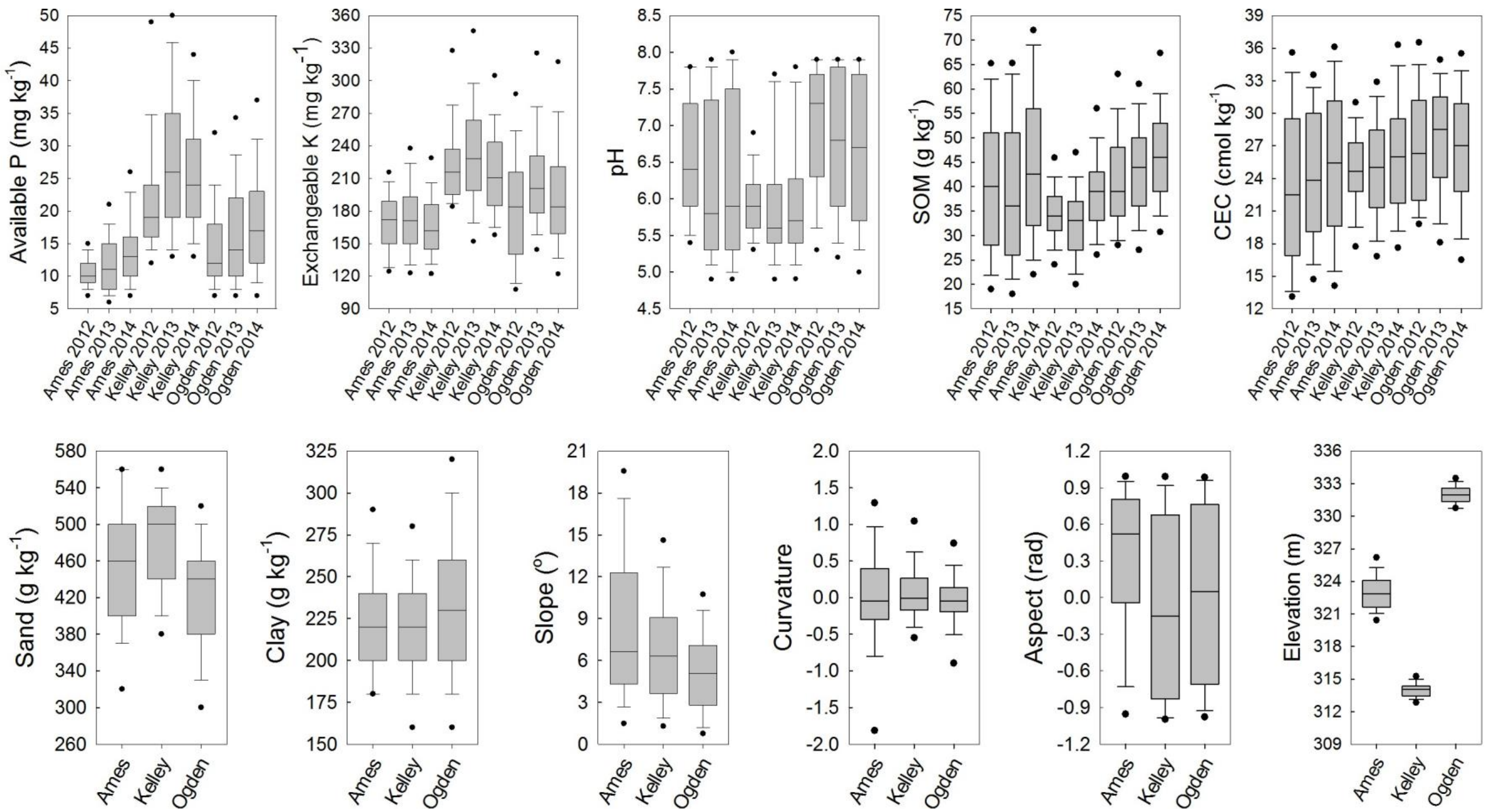

Fig. 1 Descriptive statistics of the soil variables and topographic characteristics of Ames, Kelley, and Ogden in central Iowa in 2012, 2013, and 2014. Median, line within the box; 25th/75th percentile, box; 10th/90th percentile, whiskers; 5th/95th percentile, black dot.

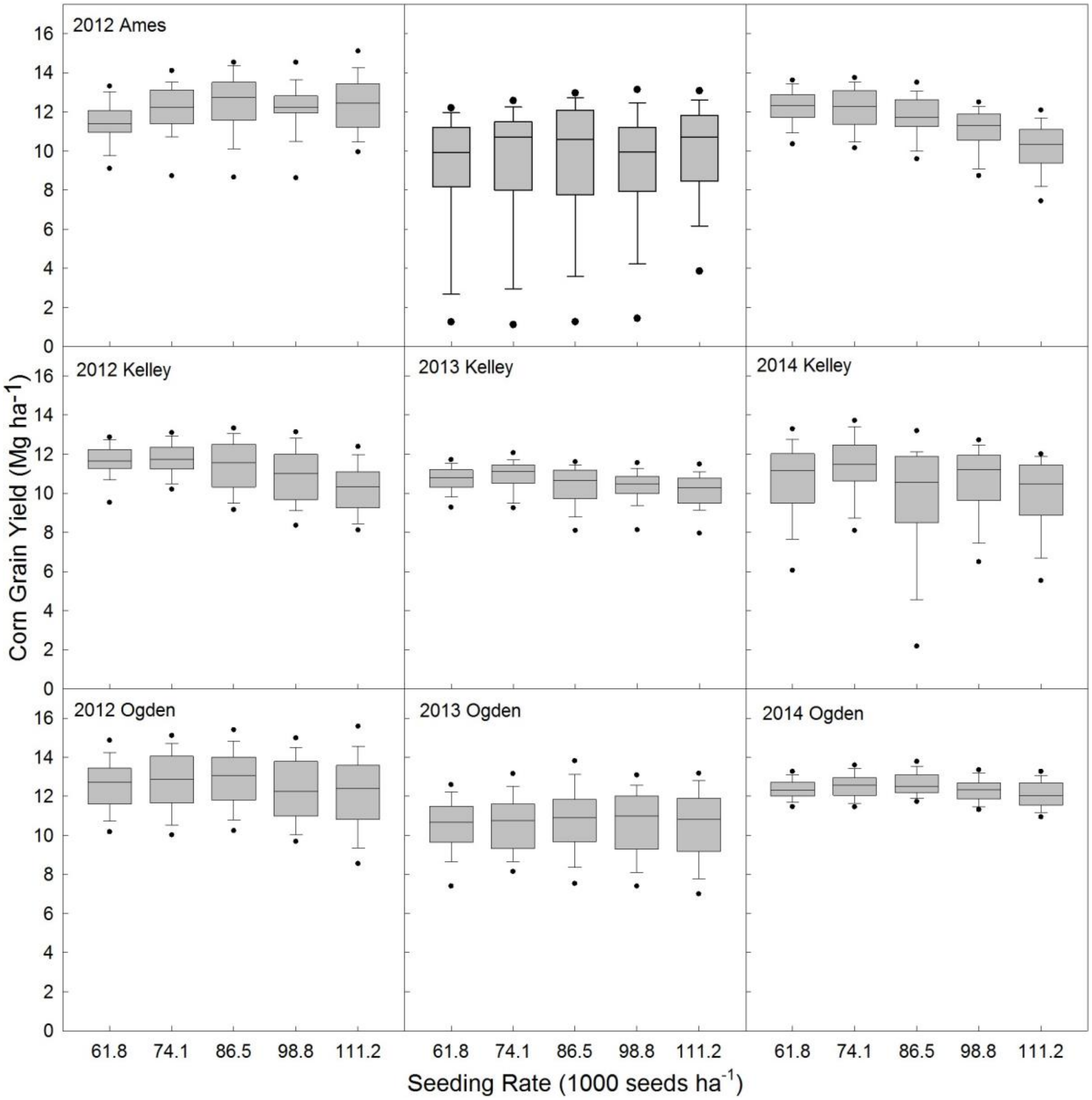

Fig. 2 Corn grain yield descriptive statistics by seeding rate for Ames, Kelley, and Ogden in 2012 to 2014. Median, line within the box; 25th/75th percentile, box; 10th/90th percentile, whiskers; 5th/95th percentile, black dot.

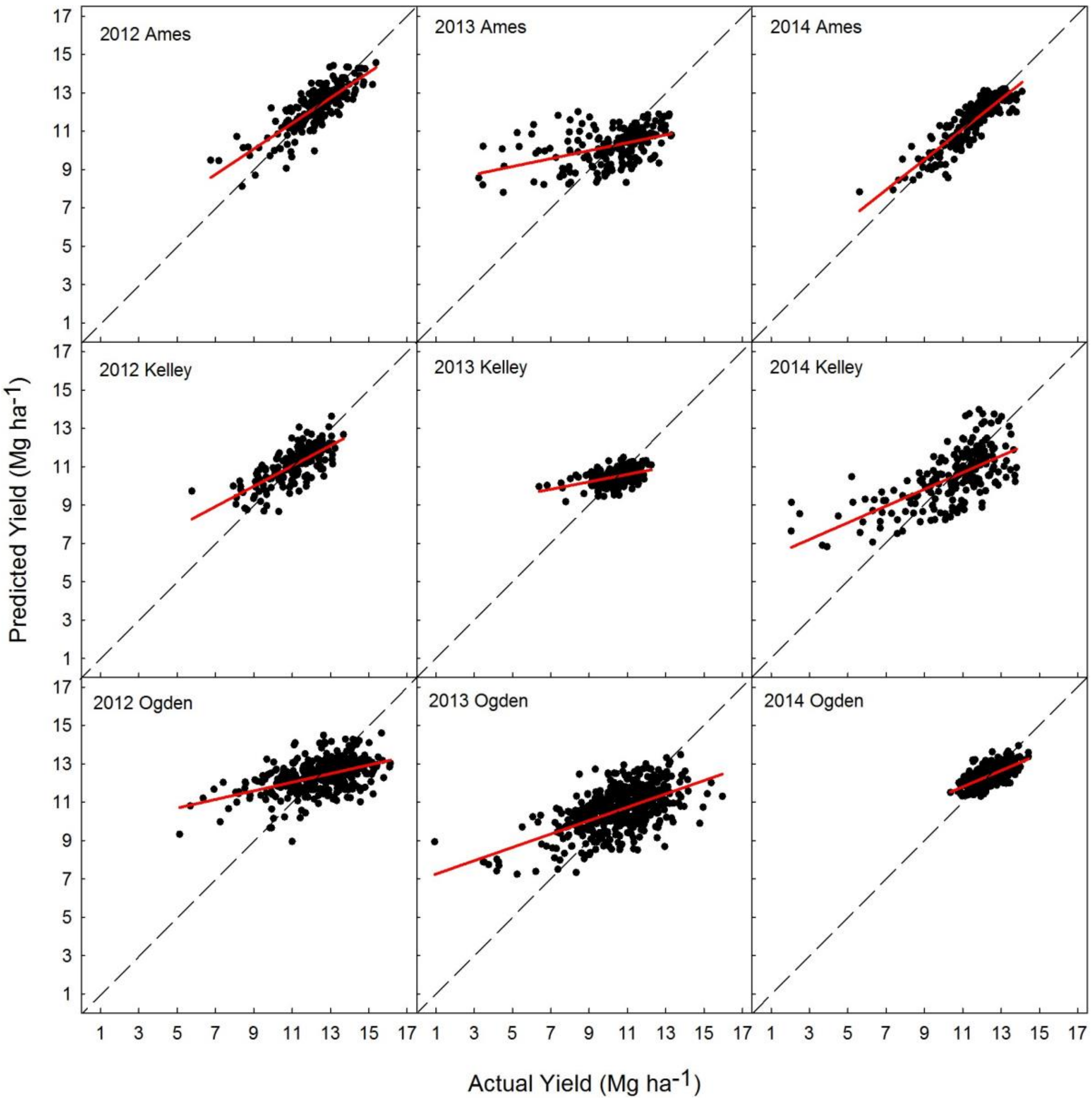

Fig. 3 Predicted versus actual yields from the reduced mixed model analysis where only soil parameters and topographic characteristics were included if there was a significant interaction with seeding rate. Dashed line represents 1:1 yield line.

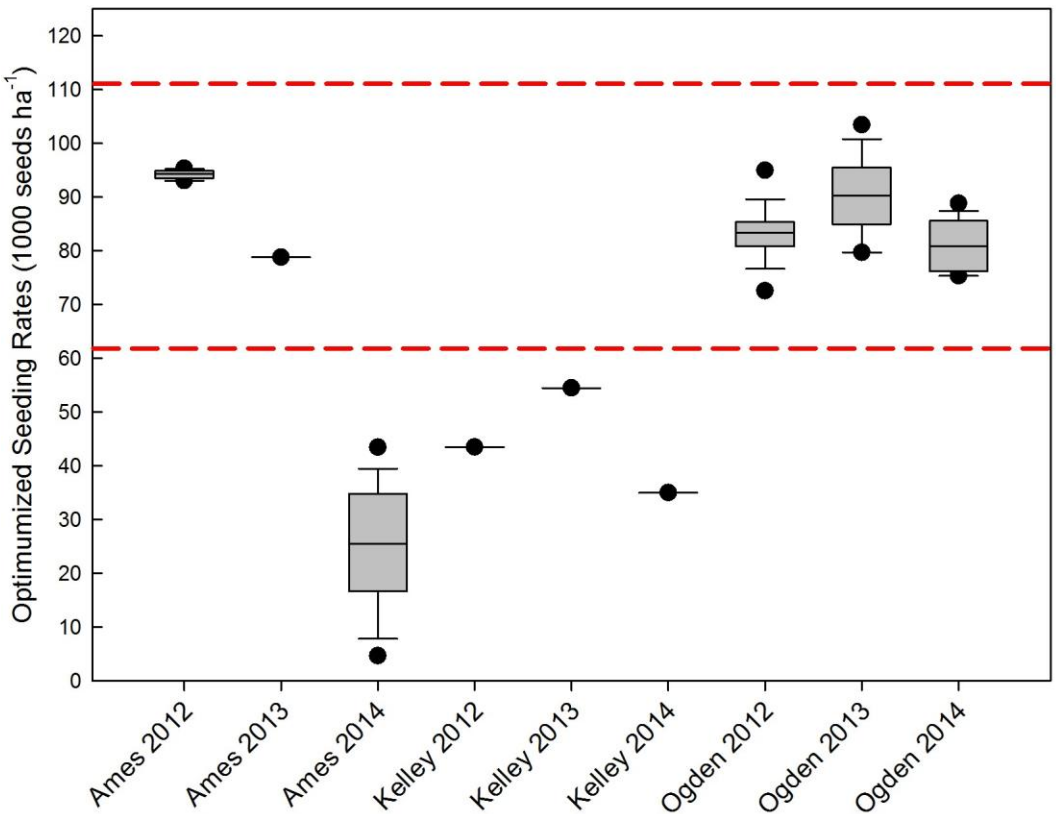

Fig. 4 Range of optimized seeding rates for each subplot of each site-year from central Iowa. Median, line within the box; 25th/75th percentile, box; 10th/90th percentile, whiskers; 5th/95th percentile, black dot; dashed line indicates upper and lower seeding rate treatment used.

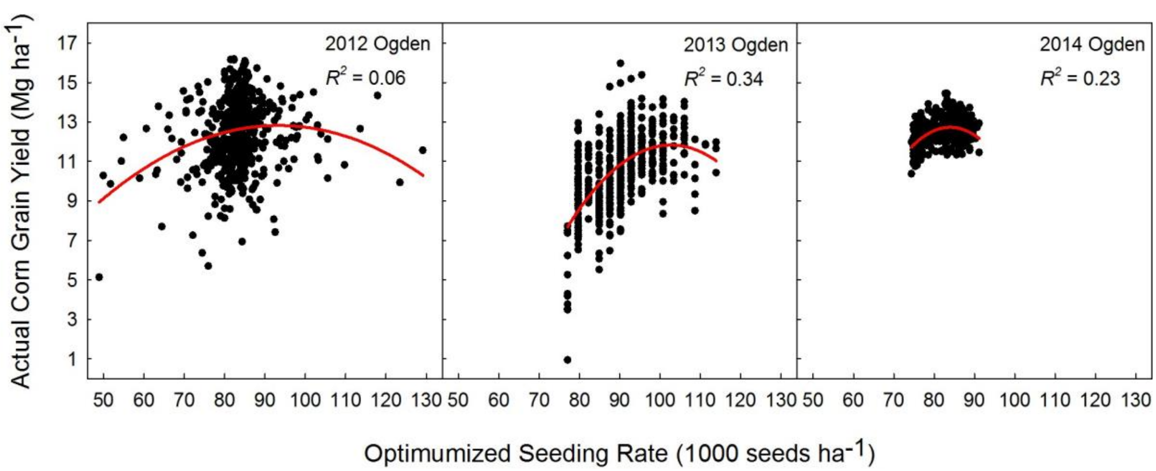

Fig. 5 Corn grain yield at the optimized seeding rate for each subplot for Ogden in 2012 to 2014.

CHAPTER 3

MAIZE SEEDING RATE, SOIL ATTRIBUTE, AND TOPOGRAPHIC CHARACTERISTIC EFFECT ON YIELD COMPONENTS

A paper for submission to Field Crops Research

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Abstract

Maize (*Zea mays* L.) grain yields in the U.S. have continued to increase since the introduction of hybrid seed corn. Currently available hybrids tolerate crowding better than hybrids from previous decades allowing for greater plant densities and associated tolerance to competition for water, nutrients, and solar radiation. Continued improvement and availability of precision technologies have increased ability to determine soil attributes and topographic characteristics within fields. Combining the ability for spatial characterization with variable rate seeding may allow targeted seeding rates for optimal productivity. This research explores soil and topographic attribute interaction with seeding rate and the effect they have on maize yield components. The study consisted of five seeding rates (61,750; 74,100; 86,450; 98,800; and 111,150 seeds ha^{-1}) in a randomized complete block design on two central Iowa fields from 2012 to 2014. Soil attributes determined were available phosphorus, exchangeable potassium, pH, soil organic matter, cation exchange capacity, and texture. Topographic data determined from Light Detection and Ranging data included in-field elevation, slope, aspect, and

curvature. Zipper ears and plant barrenness were more prevalent both as seeding rates increased but also when rainfall was limiting. Kernel weight and kernel number decreased with increases in seeding rate. There was evidence that in-field elevation combined with reliable rainfall forecasts could be used to spatially determine field areas with greater kernel weight and kernel density. Our results illustrate the importance of maize seeding rate on grain yield components but recognize that seeding rate rarely interacted with soil attributes and topographic characteristics.

1. Introduction

United States maize (*Zea mays* L.) yields have increased by 74 kg ha^{-1} yr^{-1} since the introduction of double cross and single cross hybrids (Duvick, 1997). This yield increase has come from a combination of genetic breeding for tolerance to biotic and abiotic stresses and improved use efficiency of resources with little to no grain yield per plant (GYP) gains (Duvick, 1997; Tokatlidis and Koutroubas, 2004). Maize grain yield typically responds curvilinearly with increasing plant density where seeding rate recommendations are set near the peak where maximum grain yield is achieved (Nafziger, 2012; Mueller and Sisson, 2013; Woli et al., 2014; Coulter, 2015; Lauer, 2015; Nielsen et al., 2015). At plant densities below the optimum plant density, kernel number $plant^{-1}$ (KN_P) reductions are more than compensated for by higher plant densities. Plant densities greater than the optimal plant density result in reductions in KN_P and kernel weight (KW) such that overall yield is reduced (Tetio-Kagho and Gardner, 1988; Maddonni and Otegui, 2006).

Currently available commercial hybrids are more tolerant to crowding than releases from previous decades allowing for greater plant densities and associated tolerance to competition for water, nutrients, and solar radiation (Duvick, 1997; Tollenaar and Wu, 1999; Echarte et al., 2000; Maddonni and Otegui, 2006). Over the decades that hybrid maize has been used, Duvick (1997) found kernel rows ear^{-1} (KR_E, –0.5 row 10-yr^{-1}), kernel number row^{-1} (KN_R, +0.4 kernels 10-yr^{-1}), KN_P (–11 kernels 10-yr^{-1}), KW (+0.7 g 10-yr^{-1}) and test weight (+90.7 g 10-yr^{-1}) have changed but with low coefficients of variance (0.36, 0.06, 0.11, 0.31, and 0.10 respectively).

Considerable evidence indicates that KN_P and KW decrease with increasing plant densities (Edmeades and Daynard, 1979; Baenziger and Glover, 1980; Ahmadi et al., 1993; Echarte et al., 2000; Sangoi et al., 2002; Borrás et al., 2003; Hashemi et al., 2005; Maddonni and Otegui, 2006; Boomsma et al., 2009). In addition to this evidence, use of fifty percent shade cloth amplified the reduction in KR_E, KN_P, and KW as plant density increases (Hashemi-Dezfouli and Herbert, 1992). While KN_P and KW are affected by plant density, kernel density (KD) may not be (Ahmadi et al., 1993).

Plant density can also influence maize prolificacy. Maize is usually limited to a single primary ear as plant densities increase and at high plant densities plant barrenness can occur (Tetio-Kagho and Gardner, 1988; Hashemi et al., 2005). Duvick (1997) found plant barrenness decreased at a rate of two ears 100 plants^{-1} 10 years^{-1} since the adoption of hybrid maize. This is reinforced by Sangoi et al. (2002) in Brazil where hybrids from the 1970s and 1980s experienced plant barrenness at plant densities greater than 50,000 plants ha^{-1} while hybrids released during the 1990s did not express barrenness up to 154,000 plants ha^{-1}. Similarly, in Canada, Edmeades and Daynard (1979) determined plant barrenness was limited below 100,000 plants ha^{-1} and dramatically increased above 150,000 plants ha^{-1}.

Maize yield components are influenced by genetics and the environment in addition to plant density (Stroshine et al., 1986; Yurttas, 1998). However, there is little knowledge as to how maize yield components are affected by planting density interactions with soil attributes or topographic characteristics. Boomsma et al. (2009) and Haegele et al. (2014) reported that grain yield responses to P and N are not influenced by plant densities typical of optimum maize grain yields. van Averbeke and Marais (1994) found that plant barrenness was minimal below 63,000 plants ha^{-1} and remained below ten percent up to 111,000 plants ha^{-1} in well-watered conditions but increased markedly when water was limiting at plant densities as low as 10,000 plant ha^{-1}.

As precision technologies continue to be improved and cost associated with use of precision technology becomes less expensive, farmers and agronomists have increased ability to determine soil attributes and topographic characteristics within fields. The purpose of this research was to explore how within-field variability interacts with seeding rates and the effect they have on maize yield components. The objectives of this research were to 1) determine how maize seeding rate influences yield components and 2) determine interactions among seeding rate, soil attributes, and topographic characteristics.

2. Methods

2.1. Experimental design

Field experiments were conducted over three growing seasons from 2012 to 2014 at two central Iowa, USA locations to study response of maize yield components to seeding rate across a variable landscape. The fields were under rainfed conditions in the Clarion-Nicollet-Webster soil association (Clarion [fine-loamy, mixed, mesic, Typic Hapluduolls], Nicollet [fine-loamy, mixed, mesic, Aquic Hapluduolls], and Webster [fine-loam, mixed, mesic, Typic Endoaquolls]). Both sites (Ames, 42º00'50.63"N, -093º44'24.81"W and Kelley, 41º57'09.27"N, -093º41'24.60"W) were in continuous corn production prior to and during the study. The experimental design at each site was a randomized complete block with four replications. Experimental treatments consisted of five seeding rates (61,750, 74,100, 86,450, 98,800, and 111,150 kernels ha^{-1}) planted in plots 12.2 m wide by field length of approximately 400 m long with 76.2-cm row spacing.

Field operations conducted by Iowa State University farm operations staff included fall and spring tillage, fertilizer applications, planting, herbicide applications and harvest. At both sites a disk ripper was used for primary fall tillage and a full width field cultivator for secondary spring tillage. A disc ripper is a primary tillage implement with gangs of discs cutting residue ahead of shanks breaking soil to an approximate 40 cm soil depth followed by another set of disc gangs to break and level the soil. A John Deere 7000 planter with MaxEmerge row units and a John Deere 9550 combine were used across each site-year (Deere and Company, Moline, IL). At the Ames site Pioneer hybrids P0528XR, 1161XR, and P1023AM were used in 2012, 2013, and 2014, respectively (DuPont Pioneer, Johnston, IA). At the Kelley site Channel hybrid 209-85VT3Pro was used in 2012 and Pioneer hybrids 9910XR and 34F07 were used in 2013 and 2014, respectively (Channel Seeds, St. Louis, MO). The Ames planting dates were 11 May 2012, 18 May 2013, and 7 May 2014. The Kelley planting dates were 14 May 2012, 14 June 2013, and 9 May 2014. Fields at both sites followed typical herbicide and soil fertility programs for phosphorus (P), potassium (K) and pH for the area. A target application of 224 kg N ha^{-1} was applied as a split application at planting and approximately the sixth leaf stage at Ames and as single spring pre-plant application at Kelley.

2.2. Field data collection

Eleven subplots were established 30 m apart within each seeding rate experimental unit. Subplots consisted of the center two rows of each strip by 5.3 m long and were located and marked after planting using an Ashtech MobileMapper 100 (Trimble Integrated Technologies, Sunnyvale, CA) with a GNSS antenna that connected to the Iowa Real-Time Network for real-time kinematic (RTK) global positioning at a 1-2 cm horizontal accuracy from year to year. Plant densities and ear counts were determined by counting the number of plants or ears within the entire 8.1 m^{-2} subplot. Plant densities were determined between the fourth and sixth leaf stages and harvest plant densities were collected during the dent, R5, to physiological maturity stage, R6 (Abendroth et al., 2011). Ear counts were collected at the same time as the harvest plant density. Emergence stand density percentage was calculated as spring stand density divided by seeding rate. The final stand density percentage was calculated as fall stand density divided by seeding rate. Plant barrenness was calculated as the percentage of barren plants from fall plant density.

Soil samples collected between planting and the fourth leaf stage (Abendroth et al., 2011) were a composite of 14 soil cores taken to a depth of 15 cm at the 8.1 m^{-2} subplot level. Soil nutrient and texture analyses were conducted at Midwest Laboratories, Omaha, Nebraska using standard laboratory procedures. Soil nutrient analysis included available P, exchangeable K, pH, soil organic matter (SOM), cation exchange capacity (CEC) (Dahnke, 1975; Kuo, 1996; Sumner and Miller, 1996; Kalra, 1997). The sodium bicarbonate method was used for P (Olsen et al., 1954) and the ammonium-acetate method was used for K (Helmke and Sparks, 1996). Available water holding capacity (AWC) was calculated using soil texture and SOM based on Saxton and Rawls (2006).

2.3. Grain yield and topographic spatial data

The plot area was mechanically harvested with a calibrated Integra yield monitor (Ag Leader Technology, Ames, IA) and GPS receiver to attain site-specific maize grain yield and moisture. The harvest width was 9.1 m where the center 12 rows of the 16-row plot were harvested; the second row of the plot was used for collection of ear samples. Yield monitor data were processed using SMS Basic (Ag Leader Technology Ames, IA) before exporting to ArcMap (ESRI, Redlands, CA). ArcMap was used to determine yield and grain moisture at the subplot level by creating 6m buffers around the central point of the subplot followed by a spatial join of the yield information. The buffer distance was half the plot width resulting in yield information for each subplot being an average of approximately five to seven yield monitor data points. Topographic data were generated using 0.61 m contours from the Light Detection and Ranging (LIDAR) 3 m Digital Elevation Model (DEM) of Boone and Story counties (Iowa) available from the Natural Resources Geographic Information Systems Library of the Iowa Department of Natural Resources (https://programs.iowadnr.gov/nrgislibx/). ArcMap spatial analyst tools were used to determine in-field elevation, slope, slope curvature, and slope aspect of each subplot. Positive slope curvature values result from convex slopes and negative curvature values result from concave slopes. Slope aspect identifies the direction a slope faces (0 to 360 degrees). For this analysis slope aspect was transformed to 'northness' with values of –1 to 1 where slope aspects of negative one are south facing and slopes of positive one are north facing.

2.4. Yield components

Ear samples were collected the day of combine harvest from each subplot for determination of yield components. Ear samples were collected from the second row of each plot. In 2012, 14 consecutive ears per subplot were collected and in 2013 and 2014, eight consecutive ears per subplot were collected. Yield components selected for direct determination were zipper ears, KR_E, and KW. Zipper ears are abnormal ears caused by paired spikelet collapse which results in incomplete kernel set where partial or entire kernel rows on the ear do not properly develop and pollinate (Mansfield and Mumm, 2014). Ear samples were hand processed for determination of KR_E and then shelled using an AEC small batch sheller (AEC Group, Charles City, IA). Individual KW was determined from a sub sample of the shelled grain using an OptiCount (Satake USA Inc., Stafford, TX). Whole sample weight, individual kernel weight, and ear sample count were used to calculate KN_E.

2.5. Statistical analysis

The PROC GLM procedure was used to determine the main effects and interactions of seeding rate, soil attributes, and topographic characteristics on maize yield components (SAS Institute, 2012). Location × year × seeding rate × replication were assigned as random effects in the initial model analysis. Based on an initial combined analysis it was found that location, year, and location × year interactions were significant (results not shown); thus further statistical analyses for yield components were carried out by site-year with seeding rate × replication were assigned as random effects.

3. Results

Emergence percentage differed among seeding rates four of six site-years (Table 1). Emergence percentage at Ames was lowest at the 61,750 seeds ha^{-1} seeding rate but at Kelley was improved at the higher seeding rates. Final stand percentage was different amongst seeding rates for three of six site-years. Final stand percentage decreased as seeding rate increased at Ames and Kelly in 2012. Conversely, final stand percentage decreased as seeding rate decreased at Kelley in 2014. Zipper ears were more common at higher seeding rates in all site-years. Zipper ears were more prevalent in 2012 compared to 2013 and higher in 2013 compared to 2014 for both sites (means of 20.0%, 6.2%, and 2.4%, respectively). At Ames in 2012 there was a large increase in zipper ears above 86,450 seeds ha^{-1} and above 74,100 seeds ha^{-1} at Kelley in 2012. Plant barrenness increased at the higher seeding rates in five of six site-years, especially above the 111,150 seeds ha^{-1} seeding rate

KR_E, KN_E, and KW decreased with increasing seeding rates for all site-years (Table 2). There was a mean KR_E of 15.7 across site-years with more KR_E in 2013 at Ames and Kelley (15.9 and 16.6 respectively) compared to the other site-years. The KN_E was the lowest in 2012 and greater in 2013 and 2014 at both Ames and Kelley. The mean KW was greater in 2012 compared to 2013 and 2014 (343, 283, and 258 mg seed^{-1} respectively). Kernel density was lower at the lowest seeding rates in three of six site-years whereas at Kelley in 2014 the lowest seeding rate had the highest KD (1.28 g cm^{-3}).

While seeding rate routinely influenced yield components, there was no soil attribute or topographic characteristic that consistently interacted with seeding rate to influence yield components (Tables 3 and 4). The main effect of available P and pH commonly influenced yield components. Generally, as pH increased there was a negative effect on yield components (Figs. 1 – 4) while available P did not consistently affect yield components (Figs. 5 – 7). KN_E increased with greater available P at Ames in 2012 and 2013 but decreased at Kelley in 2014 (Fig. 5). KW increased with greater available P in two site-years, decreased in one site-year, and had an optimal response curve in two site years (Fig. 6). Available P had a positive influence on KD in four site-years (Fig. 7). Additionally, in-field elevation influenced both KW and KD in three and four site-years respectively (Figs. 8 – 9). Higher in-field elevations resulted in lower KW in two site-years and higher KW in one site-year (Ames, 2014). In three site-years in-field elevation negatively influenced KD. AWC resulted in a peak KN_E at approximately 0.14 cm cm^{-3} AWC at Ames and Kelley in 2012 but had a slightly negative response at Ames in 2014 (Fig. 10). There was also a quadratic KD response to CEC in four site-years (Fig. 11). The quadratic responses resulted in peak KD at 19.0, 30.5, 14.3, and 33.3 for Ames in 2012, Ames in 2013, Kelley in 2013, and Kelley in 2014 respectively.

4. Discussion

When considering the impact of seeding rate on yield components it is important to consider both success of seedling emergence and survivability to harvest (Table 1). In 2012 at both locations, there was a reduction in stand percentage from early season to late season. This was most notable at seeding rates of 86,450 seeds ha^{-1} and above. The likely reason for this reduction at the higher seeding rates is due competition for soil water in a drought year. This phenomenon was not realized in 2013 and 2014 when rainfall was more plentiful.

Two indicators that ideal plant densities are achieved are the number of zipper ears and plant barrenness, especially at the highest seeding rates (Table 1). Zipper ears were more common at higher seeding rates but were also affected by growing season conditions. The abundance of zipper ears was affected by rainfall and temperature conditions more so than by soil attributes or topographic characteristics. In 2012, the abundance of zipper ears was greatest at both locations; this year was abnormally dry with warmer temperatures during pollination and the early grain fill period. Whereas in 2013 and 2014 when zipper ear numbers were lower at both locations, there was adequate rainfall and soil moisture along with cooler than normal temperatures through the early grain fill period. Plant barrenness increased with seeding rate at three of six site-years but, in contrast to van Averbeke and Marais (1994), seemed not to be affected by AWC. In our study there was only one site-year where an AWC interaction with seeding rate affected plant barrenness (Kelley, 2013).

Maize seeding rate affects grain yield components. In our study, increasing seeding rates resulted in decreased KW, KR_E, and KN_E (Table 2). The effect of seeding rate on yield components confirms previous reports that individual plant yields are reduced as plant densities increase but overall grain yield is increased due to an increased number of plants (Tetio-Kagho and Gardner, 1988; Maddonni and Otegui, 2006).

While seeding rate consistently influenced yield components, soil attribute or topographic characteristic interactions with seeding rate did not consistently influence yield components (Tables 3 and 4). The main effects from soil attributes that most consistently influenced yield components were pH and available P as well as CEC and AWC to a lesser extent. Increased soil pH resulted in negative responses by yield components, however, regressions indicate low coefficients of variation (generally $\leq$ 0.10). Whereas, available P inconsistently influenced yield components. Haegele et al. (2014) found that P fertilization increased KN_E and KW in 2010 but only KN_E in 2011.

Soil attributes and topographic characteristics that aid in the retention or dispersal of rainfall, such as in-field elevation and AWC, were useful to explain yield components when the environmental conditions were considered. Under dry conditions, lower in-field elevations and greater AWC resulted in increased KN_E or KW, likely due to greater water availability. In wetter conditions, such as Ames in 2014, higher in-field elevations resulted in greater KW. Combined, these findings indicate that soil attributes and topographic characteristics such as in-field elevation do influence yield components and, therefore, grain yields. These findings agree with previous research that reported grain yield is influenced by topographic characteristics and the ability of soils to hold or drain water (Kravchenko and Bullock, 2000; Kravchenko et al., 2003; Kaspar et al., 2004; Shanahan et al., 2004).

5. Conclusions

Our results document the importance of maize seeding rate on grain yield components but seeding rate interactions with soil attributes and topographic characteristics were not good predictors of yield component response. Kernel weight and kernel number ear^{-1} decreased with increases in seeding rate. Zipper ears were more prevalent both as seeding rates increased and when rainfall was limited. Furthermore, there is evidence that soil available P and pH can influence yield components but are not good predictors of yield components. Additional research needs to be conducted to identify and better understand how maize seeding rate and environment interactions are affected by soil fertility, soil texture, and topography across a larger geographic area with more diverse soils and topographic characteristics.

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Table 1 Percent emergence, final stand, plant barrenness, and zipper ear occurrence by seeding rate at Ames and Kelley from 2012 to 2014.

Site	Year	Seeding rate	Emergence stand density	Final stand density	Zipper ears	Plant barrenness
		seeds ha^{-1}	%	%	%	%
Ames	2012	61,750	90.0b	90.5bc	3.69c	1.5c
		74,100	94.2a	94.3a	6.36c	3.1b
		86,450	94.1a	92.3b	14.48b	3.0b
		98,800	92.3a	89.4c	17.59ab	3.5b
		111,150	92.3a	89.6c	20.21a	5.3a
		Pr > F	**	***	***	***
	2013	61,750	69.5	69.9	2.00b	2.2b
		74,100	69.2	66.4	3.54b	2.8b
		86,450	71.8	72.2	6.57b	3.9b
		98,800	68.2	62.8	12.66a	3.7ab
		111,150	74.2	68.4	13.36a	6.4a
		Pr > F	NS	NS	***	*
	2014	61,750	97.3b	97.8c	0.30c	0.5c
		74,100	99.6ab	101.4a	0.59c	1.1c
		86,450	99.8ab	99.0b	0.00c	0.9c
		98,800	101.2a	99.5b	3.20b	2.1b
		111,150	100.4a	99.4b	7.00a	3.5a
		Pr > F	*	*	***	***
Kelley	2012	61,750	91.5	95.6a	5.60d	12.7ab
		74,100	93.6	88.3b	17.78c	7.0c
		86,450	90.7	86.5b	22.98c	8.8bc
		98,800	91.5	83.2c	37.09b	8.1c
		111,150	91.4	81.8c	54.63a	11.8a
		Pr > F	NS	***	***	**
	2013	61,750	97.0d	97.0	0.89d	3.3
		74,100	99.7bc	98.1	1.18cd	3.6
		86,450	98.9cd	95.8	6.09b	3.4
		98,800	102.0a	98.5	4.98bc	4.0
		111,150	101.6ab	98.6	10.70a	3.5
		Pr > F	***	NS	**	NS
	2014	61,750	92.6c	93.7b	0.60b	1.3d
		74,100	94.7b	94.7ab	0.89b	1.9cd
		86,450	96.2ab	95.9a	2.88b	3.2bc
		98,800	95.1ab	95.4a	2.86b	3.7b
		111,150	96.7a	96.0a	5.50a	5.1a
		Pr > F	***	*	***	***

Note: Means within followed by different lowercase letters are significant at the $p \leq 0.05$ probability level for seeding rate within a site-year; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

Table 2 Corn yield component means by seeding rate at Ames and Kelley from 2012 to 2014.

Site	Year	SR	KR_E	KN_E	KW	KD
		seeds ha^{-1}			mg	g cm^{-3}
Ames	2012	61,750	14.99a	562a	326a	1.293
		74,100	14.74ab	507b	313b	1.295
		86,450	14.51bc	472c	303c	1.298
		98,800	14.48c	439d	295d	1.299
		111,150	14.27d	404e	290d	1.300
		Pr > F	***	***	***	NS
	2013	61,750	16.08a	593a	336a	1.283
		74,100	16.03a	547b	320b	1.281
		86,450	15.96ab	493c	307c	1.279
		98,800	15.78b	441d	307c	1.280
		111,150	15.77b	409d	310bc	1.281
		Pr > F	*	***	***	NS
	2014	61,750	15.31a	581a	327a	1.260c
		74,100	15.29a	562a	290b	1.261bc
		86,450	15.11a	503b	267c	1.261bc
		98,800	14.88b	467c	242d	1.266a
		111,150	14.65c	410d	232e	1.265ab
		Pr > F	***	***	***	*
Kelley	2012	61,750	16.31a	518a	390a	1.261d
		74,100	16.08a	454b	385ab	1.264cd
		86,450	15.80b	422c	383b	1.268bc
		98,800	15.38b	361d	373c	1.272b
		111,150	14.98c	311e	367d	1.277a
		Pr > F	***	***	***	***
	2013	61,750	16.72a	618a	280a	1.240c
		74,100	16.79a	562b	256b	1.245bc
		86,450	16.61ab	501c	245c	1.251a
		98,800	16.46bc	453d	241cd	1.245bc
		111,150	16.35c	422e	233d	1.247ab
		Pr > F	**	***	***	**
	2014	61,750	16.46a	625a	287a	1.282a
		74,100	16.48a	607a	259b	1.276b
		86,450	16.15b	529b	237c	1.278ab
		98,800	16.31ab	541b	224d	1.275b
		111,150	15.88c	487c	211e	1.276b
		Pr > F	***	***	***	**

Note: SR, seeding rate; KR_E, kernel rows ear^{-1}; KN_E, kernel number ear^{-1}; KW, kernel weight; KD, kernel density. Means within followed by different lowercase letters are significant at the $p \leq 0.05$ probability level for seeding rate within a site-year; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

Table 3 Significance of seeding rate, soil attribute, and topographic characteristic main effects and interactions on KR_E and KN_E for each site-year.

	KR_E						KN_E					
	Ames			Kelley			Ames			Kelley		
Variable	2012	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
SR	***	*	***	***	**	***	***	***	***	***	***	***
P	NS	NS	NS	NS	NS	NS	***	**	NS	NS	NS	**
P × SR	*	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS
K	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS
K × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH	NS	NS	***	**	*	*	**	NS	**	*	NS	*
pH × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CEC	NS	NS	NS	NS	NS	NS	NS	***	NS	NS	*	NS
CEC × SR	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
SOM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
SOM × SR	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
S_a	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
S_a × SR	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
C_l	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
C_l × SR	NS	*	NS	NS	NS	NS	*	*	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	**
C × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
A	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
A × SR	NS	*	NS	NS	*	NS	NS	NS	NS	NS	NS	NS
E	NS	NS	NS	NS	*	NS	*	NS	NS	NS	NS	NS
E × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
AWC	NS	NS	NS	NS	NS	NS	*	NS	*	**	NS	NS
AWC × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: KR_E, kernel rows ear^{-1}; KN_R, kernel number row^{-1}; SR, seeding rate; P, available phosphorus; K, exchangeable potassium; CEC, cation exchange capacity; SOM, soil organic matter; S_a, sand content; S_i, silt content; C_l, clay content; S, slope percentage; C, slope curvature; A, slope aspect; E, elevation; AWC, plant available water capacity; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

Table 4 Significance of seeding rate, soil attribute, and topographic characteristic main effects and interactions on KW and KD for each site-year.

	KW						KD					
	Ames			Kelley			Ames			Kelley		
	2012	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
SR	***	***	***	***	***	***	NS	NS	*	***	**	**
P	***	*	NS	**	**	***	NS	**	*	NS	*	**
P × SR	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
K	NS	NS	***	NS	**	NS	NS	NS	NS	NS	NS	NS
K × SR	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH	***	NS	***	NS	NS	***	**	NS	**	**	**	NS
pH × SR	NS	NS	NS	NS	**	*	NS	NS	NS	NS	NS	NS
CEC	NS	NS	NS	NS	**	NS	**	*	NS	NS	**	**
CEC × SR	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	**	NS
SOM	NS	**	NS	NS	NS	NS	NS	**	NS	NS	NS	NS
SOM × SR	NS	NS	NS	*	NS	NS	NS	NS	**	NS	NS	NS
S_a	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
S_a × SR	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
C_l	*	**	NS	NS	NS	NS	*	**	NS	NS	NS	NS
C_l × SR	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
S	NS	NS	NS	**	*	NS	NS	*	NS	NS	NS	**
S × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	***	NS	***	NS	**	NS	NS	NS	**
C × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
A	NS	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS
A × SR	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
E	*	NS	*	*	NS	NS	NS	**	NS	*	*	*
E × SR	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
AWC	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**
AWC × SR	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: KW, kernel weight; KD, kernel density; SR, seeding rate; P, available phosphorus; K, exchangeable potassium; CEC, cation exchange capacity; SOM, soil organic matter; S_a, sand content; S_i, silt content; C_l, clay content; S, slope percentage; C, slope curvature; A, slope aspect; E, elevation; AWC, plant available water capacity; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

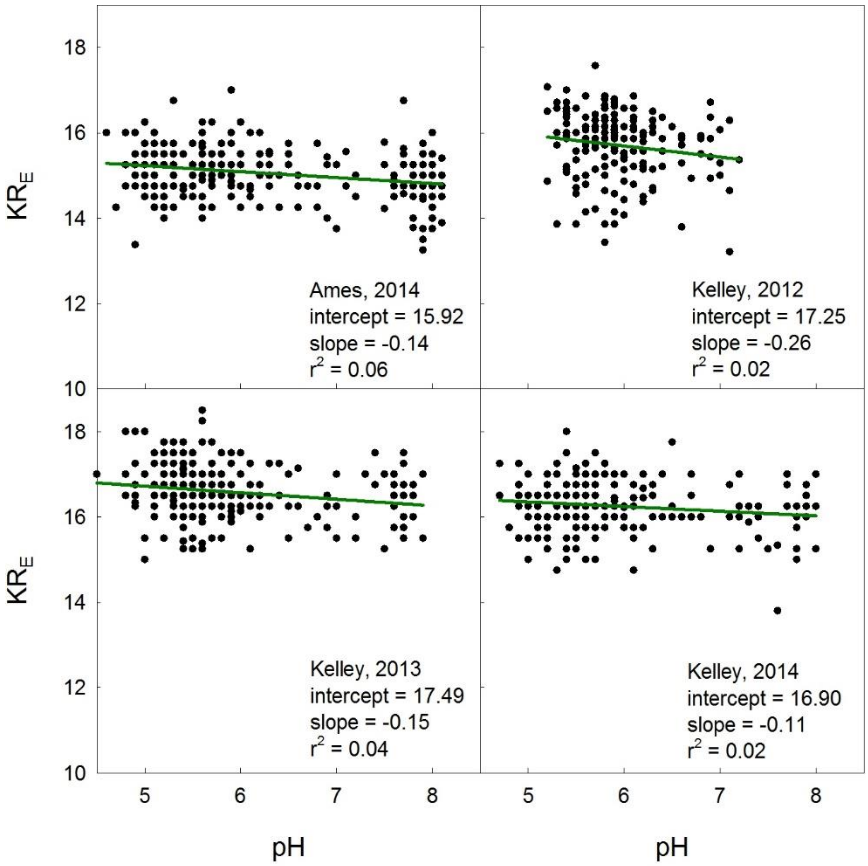

Fig. 1. Kernel rows ear^{-1} (KR_E) response to pH for Ames in 2014 (top left), Kelley in 2012 (top right), Kelley in 2013 (bottom left), and Kelley in 2014 (bottom right).

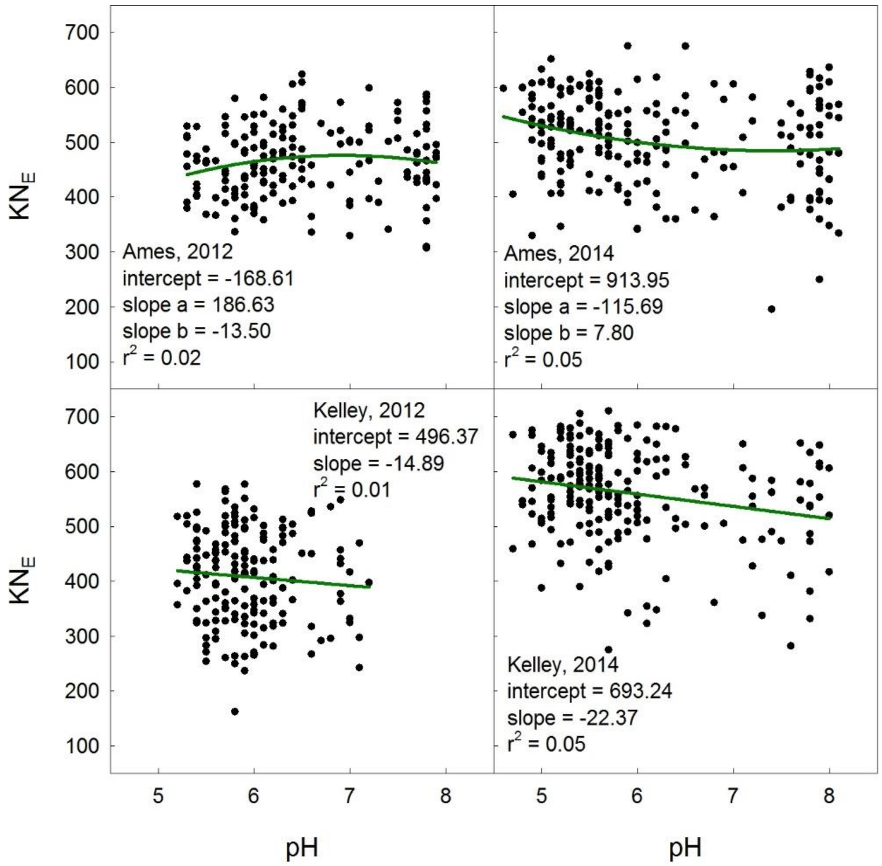

Fig. 2. Kernel number ear^{-1} (KN_E) response to pH for Ames in 2012 (top left), Ames in 2014 (top right), Kelley in 2012 (bottom left), and Kelley in 2014 (bottom right).

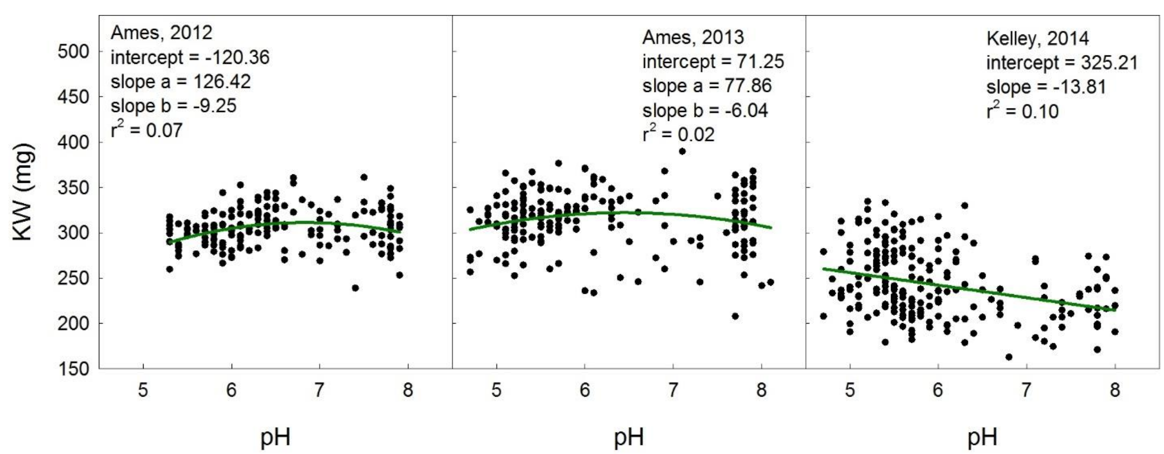

Fig. 3. Kernel weight (KW) response to pH for Ames in 2012 (left), Ames in 2013 (center), and Kelley in 2014 (right).

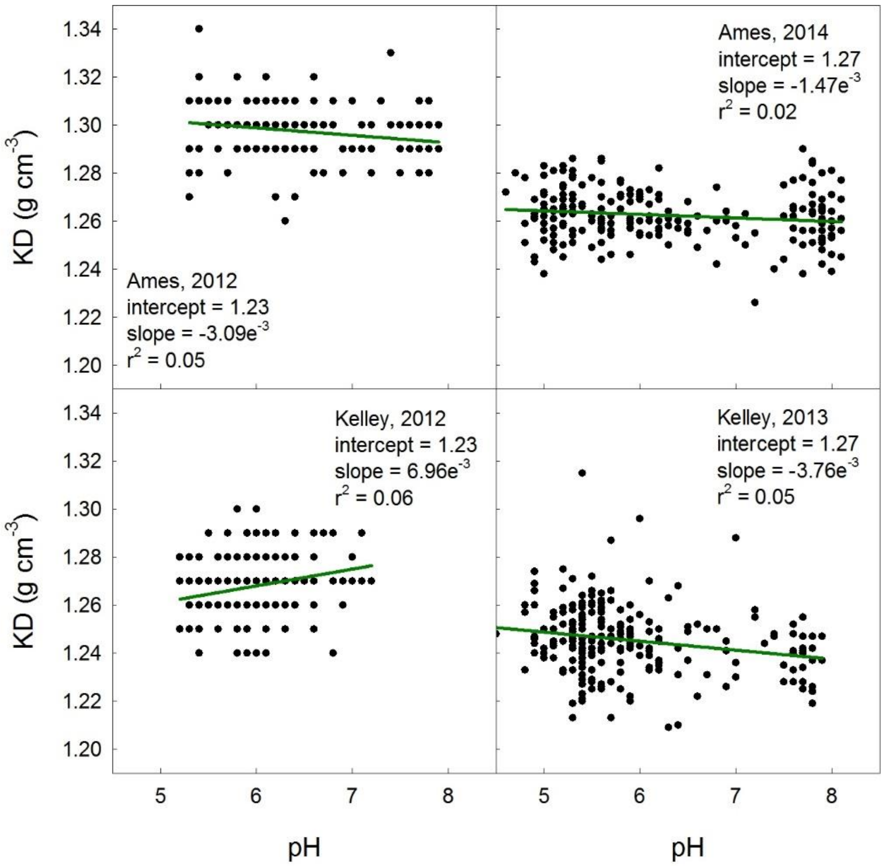

Fig. 4. Kernel density (KD) response to pH for Ames in 2012 (top left), Ames in 2014 (top right), Kelley in 2012 (bottom left), and Kelley in 2013 (bottom right).

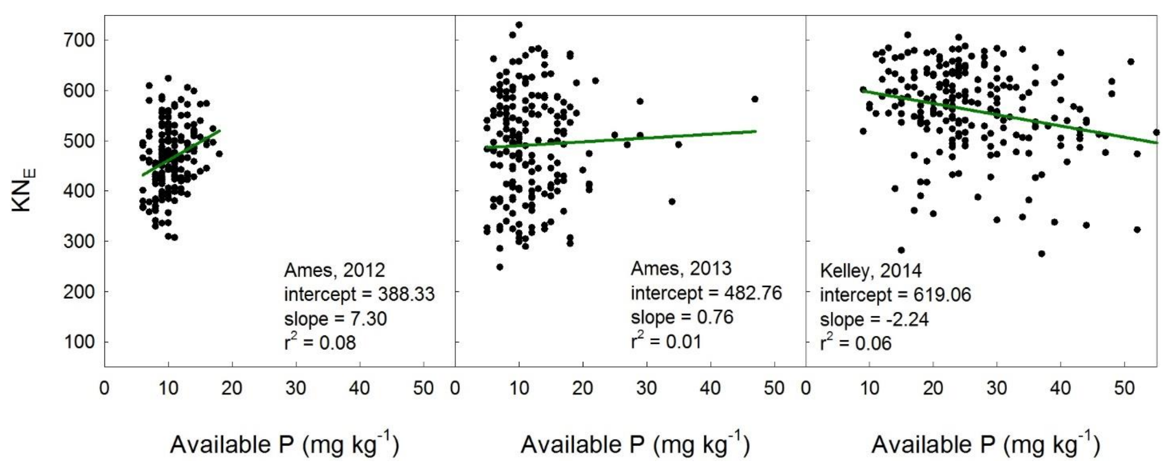

Fig. 5. Kernel number ear^{-1} (KN_E) response to available P for Ames in 2012 (left), Ames in 2013 (center), and Kelley in 2014 (right).

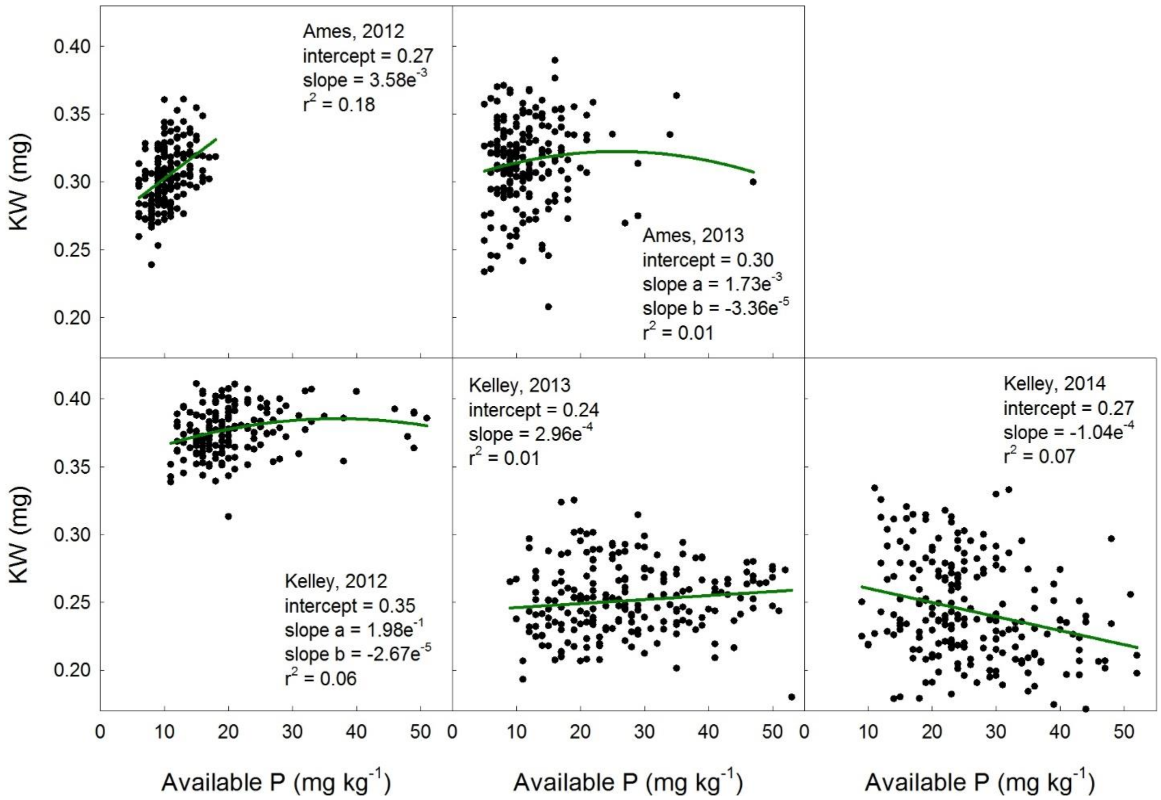

Fig. 6. Kernel weight (KW) response to available P for Ames in 2012 (top left), Ames in 2013 (top right), Kelley in 2012 (bottom left), Kelley 2013 (bottom center), and Kelley in 2014 (bottom right).

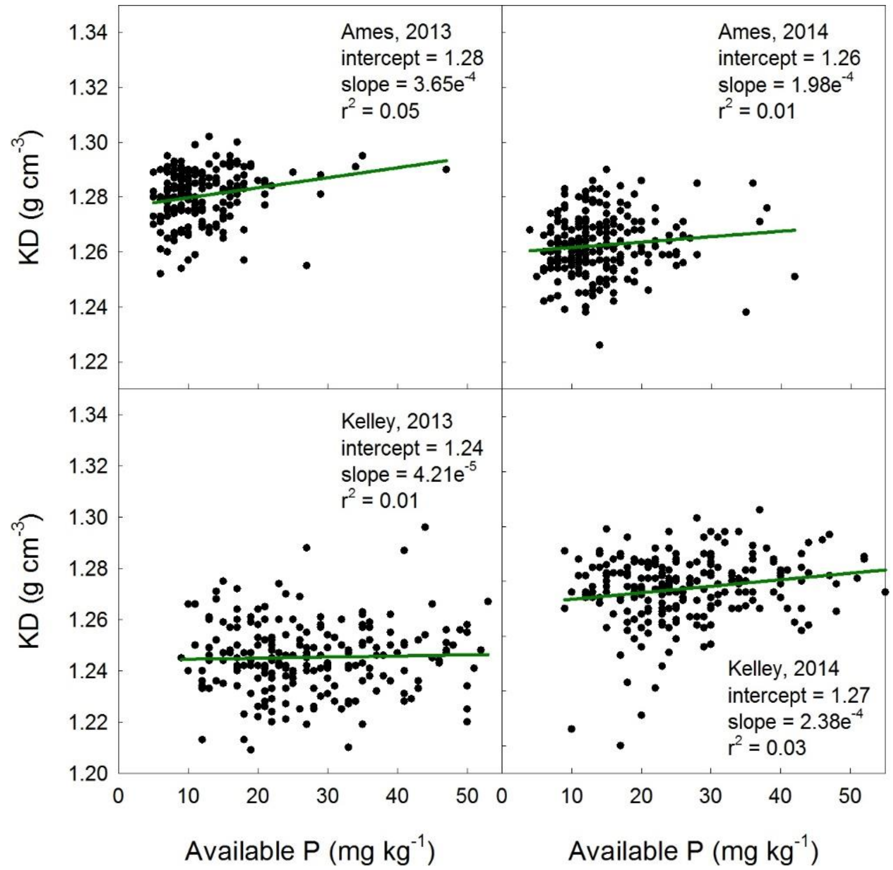

Fig. 7. Kernel density (KD) response to available P for Ames in 2013 (top left), Ames in 2014 (top right), Kelley in 2013 (bottom left) and Kelley in 2014 (bottom right).

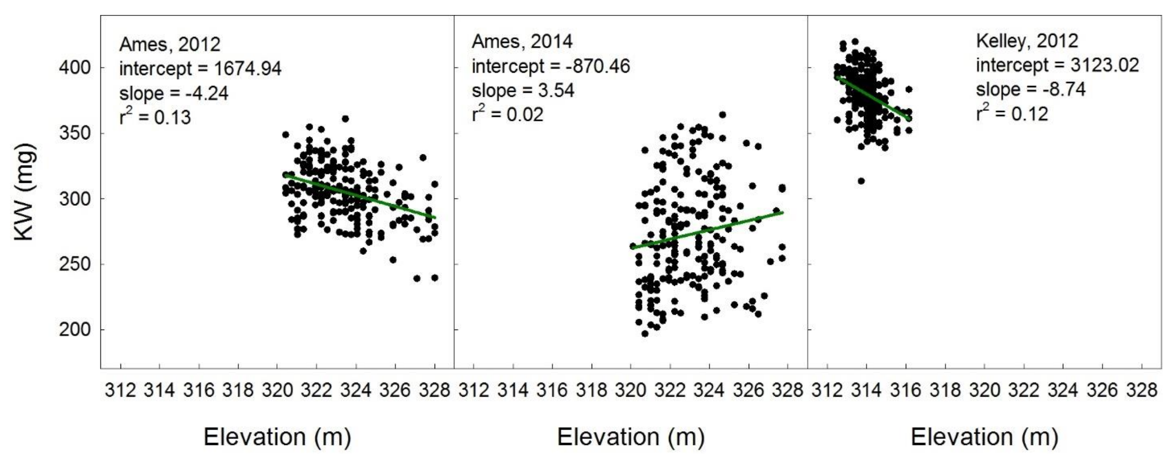

Fig. 8. Kernel weight (KW) response to in-field elevation for Ames in 2012 (left), Ames in 2014 (center), and Kelley in 2012 (right).

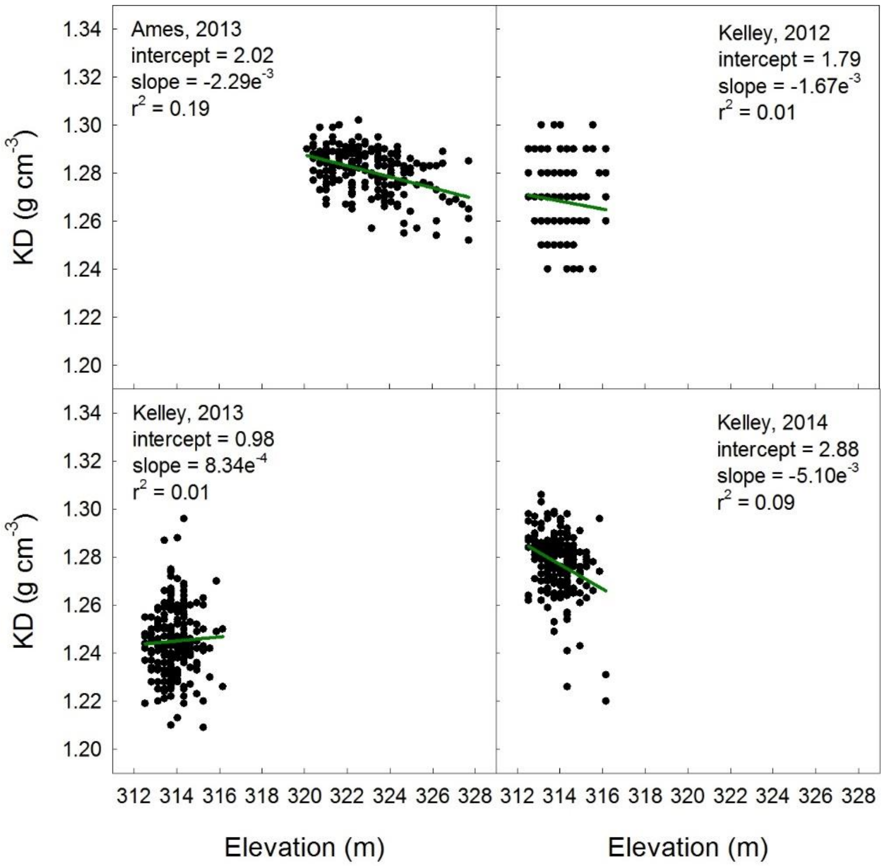

Fig. 9. Kernel density (KD) response to in-field elevation for Ames in 2013 (top left), Kelley in 2012 (top right), Kelley in 2013 (bottom left), and Kelley in 2014 (bottom right).

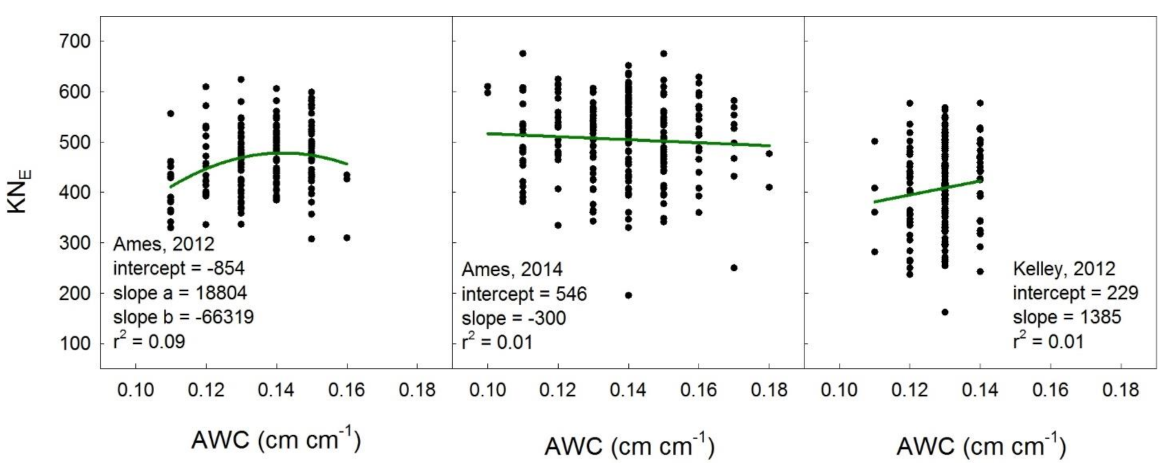

Fig. 10. Kernel number ear^{-1} (KN_E) response to available water holding capacity (AWC) for Ames in 2012 (left), Ames in 2014 (center), and Kelley in 2012 (right).

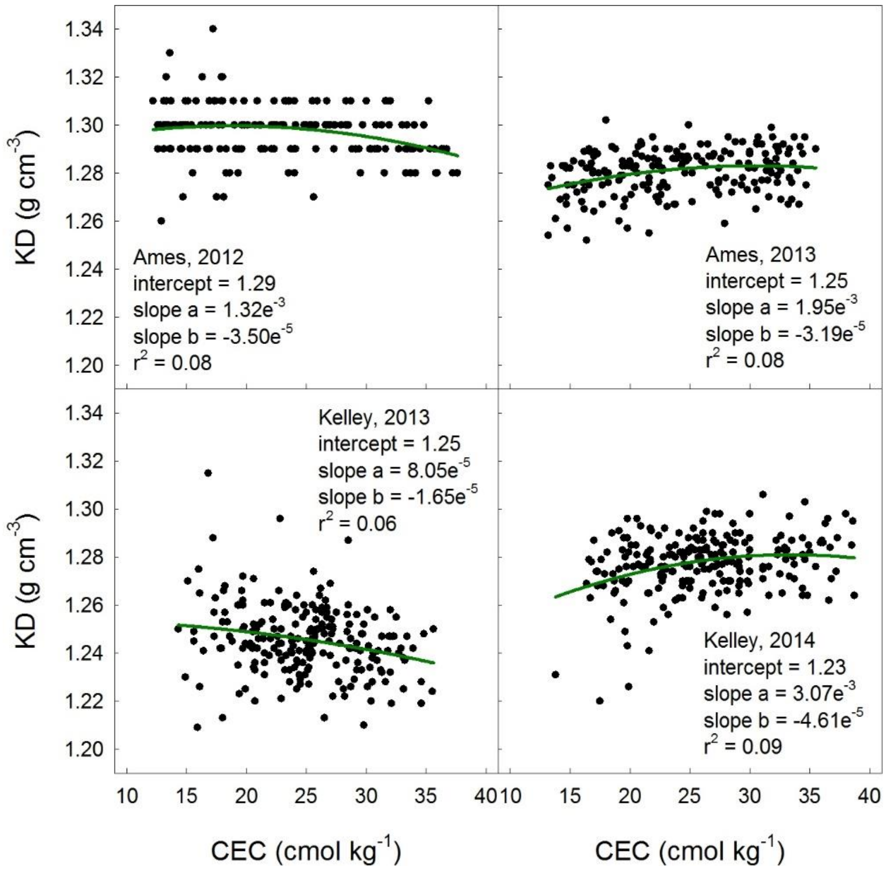

Fig. 11. Kernel density (KD) response to cation exchange capacity (CEC) for Ames in 2012 (top left), Ames in 2013 (top right), Kelley in 2013 (bottom left), and Kelley in 2014 (bottom right).

CHAPTER 4.

MAIZE SEEDING RATE, GRAIN YIELD, SOIL ATTRIBUTE, AND TOPOGRAPHIC EFFECTS ON GRAIN COMPOSITION

A paper for submission to Field Crops Research

Mark A Licht, Andrew W. Lenssen, and Roger W. Elmore

Abstract

Maize (*Zea mays* L.) grain is widely used in the livestock and ethanol industries in Iowa, USA. Due to the volume of the maize supply used, maintaining grain composition quality is important. The objective of this research was to determine how seeding rate, soil attributes, and topographic characteristics influence grain protein, oil, and starch concentrations. The study consisted of five maize seeding rates (61,750; 74,100; 86,450; 98,800; and 111,150 seeds ha^{-1}) in a randomized complete block design on two central Iowa fields from 2012 to 2014. Soil attributes determined were available phosphorus (P), exchangeable potassium (K), pH, soil organic matter (SOM), cation exchange capacity (CEC), and texture. Topographic data determined from Light Detection and Ranging (LIDAR) data included in-field elevation, slope, aspect, and curvature. Seeding rate did not influence grain composition and only infrequently interacted with soil attributes and topographic characteristics to influence grain composition. Maize grain yield always explained more of the variation in grain

composition than the selected soil attributes and topographic characteristics examined but even grain yield was limited in usefulness.

1. Introduction

Most of the commodity maize grain produced in the United States is used for feeding livestock (128.0 million metric tons) or ethanol (130.2 million metric tons) production (USDA-ERS, 2015). The distillers grains coproduct from ethanol production is also used as feed for livestock production. Both the grain ethanol and livestock industry rely mainly on grain starch within the kernel but because of the quantity of maize used in livestock production it is also a major source of protein (Loy and Wright, 2003). Maintaining maize grain composition at levels necessary to support the livestock and ethanol industries is important as maize production management practices evolve.

It has long been understood that weather, genetics, soils and soil fertility as well as harvest, drying and storage logistics influence maize grain composition (Miller and Brimhall, 1951; Earle, 1977; Alexander, 1988; Bullock et al., 1989; Nugteren, 1999; White and Johnson, 2003; Miao et al., 2006b). Both maize grain yield and protein concentration respond positively to increased N fertilizer rates while grain oil and starch concentration respond negatively to additional N (Pierre et al., 1977; Thomison et al., 2004; Miao et al., 2006b). Other research found that while grain protein was influenced by genotype, soil fertility, and their interaction, there was little to no response of grain oil to fertilizer applications of nitrogen (N), phosphorus (P), or potassium (K) (Zuber et al., 1954; Genter et al., 1956; Welch, 1969). Grain oil concentration is highly heritable

(White and Johnson, 2003) hence hybrid selection and, to a lesser degree, environment have a greater influence on grain oil as compared to grain protein (Genter et al., 1956; Jellum and Marion, 1966; Miao et al., 2006b).

Miao et al. (2006a) recognized the need for understanding the spatial response of grain composition to changing N fertilizer rates and hybrids because precision agriculture practices were being adopted by farmers. Nearly a decade later there still is minimal knowledge on the spatial variability of maize grain composition. To address spatial dependency on grain composition there is a need to understand how or if soil properties and topographic characteristics influence grain composition. In Minnesota and Iowa, Nugteren (1999) concluded that grain protein concentration was greater in well-drained, upper landscape positions compared to lower, wetter landscape positions. Grain oil concentration was most affected by slope and aspect; steeper and south facing slopes had the greatest oil concentrations in the grain. It was also determined that a lack of soil moisture resulted in low starch concentrations.

Grain composition is often correlated with yield productivity levels. Hopkins (2001) found grain oil concentration was positively correlated with soil moisture levels and at higher landscape positions with low to moderate yield productivity levels. Like grain oil concentration, protein concentration was positively correlated with soil moisture level but higher protein levels were associated with moderate to high yield productivity levels. Nugteren (1999) documented a positive grain yield correlation with grain protein (0.77) and grain oil (0.33). In contrast, starch had a negative correlation with yield (–0.70).

Maize grain yields have increased in the U.S. Corn Belt since the 1940s and simultaneously seeding rates have increased (Duvick, 2005). Maize plant densities in Iowa have increased from 64,247 plants hectare^{-1} in the early 2000s to 90,687 plants hectare^{-1} in 2014 with similar increases across the major maize growing states (USDA-NASS, 2015). While grain yields have steadily increased, there is little known on how plant densities affect maize grain composition. Increased maize plant densities result in lower grain protein concentration (Stickler, 1964; Sander et al., 1987; Ahmadi et al., 1993). However, Verma and Singh (1976) did not find a response of grain composition to seeding rate but both Genter et al. (1956) and Zuber et al. (1954) reported that when seeding rate and N fertilizer rate increased, grain protein concentration would also increase.

With continued interest in using precision technologies and spatial information as the basis for variable seeding rate applications it is important to understand how corn seeding rate and its interaction with soil attributes and topographic characteristics influence grain composition. The objective of this research was to determine 1) the impact of selected soil attributes and topographic characteristics on maize grain composition and 2) how seeding rates may influence maize grain composition.

2. Methods

2.1. Experimental design

Field experiments were conducted over three growing seasons from 2012 to 2014 at two locations in central Iowa, USA to study maize grain composition response to seeding rate across the landscape. The fields were under rainfed conditions in the Clarion-Nicollet-Webster soil association (Clarion [fine-loamy, mixed, mesic, Typic Hapluduolls], Nicollet [fine-loamy, mixed, mesic, Aquic Hapluduolls], and Webster [fine-loam, mixed, mesic, Typic Endoaquolls]). Both sites (Ames, 42^{o}00’50.63”N, -093^{o}44’24.81”W and Kelley, 41^{o}57’09.27”N, -093^{o}41’24.60”W) were in a continuous maize rotation prior to and during the study. The experimental design at each site was a randomized complete block with four replications. Experimental treatments consisted of five seeding rates (61,750, 74,100, 86,450, 98,800, and 111,150 kernels ha^{-1}) planted in plots 12.2 m wide by field length of approximately 400 m long with 76.2 cm row spacing.

Field operations were conducted by Iowa State University farm operations staff and included fall and spring tillage, fertilizer applications, planting, herbicide applications and harvest. At both sites a disc ripper was used for primary fall tillage and a full width field cultivator for secondary tillage in the subsequent spring. A disc ripper is a primary tillage implement with gangs of discs cutting residue ahead of shanks breaking soil to an approximate 40 cm soil depth followed by another set of disc gangs to break and level the soil. A John Deere 7000 planter equipped with MaxEmerge row units and a

John Deere 9550 combine were used for mechanical harvesting (Deere and Company, Moline, IL, USA). At the Ames site Pioneer hybrids P0528XR, 1161XR, and P1023AM were used in 2012, 2013, and 2014, respectively (DuPont Pioneer, Johnston, IA). At the Kelley site Channel hybrid 209-85VT3Pro was used in 2012 and Pioneer hybrids 9910XR and 34F07 were used in 2013 and 2014 (Channel Seeds, St. Louis, MO). These hybrids were chosen as commonly grown hybrids for commercial commodity production in Iowa, USA. The Ames planting dates were 11 May 2012, 18 May 2013, and 7 May 2014. The Kelley planting dates were 14 May 2012, 14 June 2013, and 9 May 2014.

Fields at both sites followed typical herbicide and soil fertility programs for P, K, and pH for continuous maize production in Iowa. A target application of 224 kg N ha^{-1} was applied as a split application at planting and approximately the sixth leaf stage at Ames and as single spring pre-plant application at Kelley. Precipitation and air temperature data were collected from Daymet Software version 2.0 (Thornton et al., 2015) for summation of monthly and growing season precipitation and accumulated growing degree days (GDD) for each site-year and 30-year means for each site (Tables 2 and 3). Dayment interpolates and extrapolates daily weather parameters using weather observations, digital elevation models, algorithms, and computer software to produce 1 km by 1 km surface grids.

2.2. Field data collection

Eleven subplots were established 30 m apart within each seeding rate experimental unit. Subplots were located and marked using an Ashtech MobileMapper

100 (Ashtech Corporation., Cleveland, OH) with a GNSS antenna that connected to the Iowa Real-Time Network for real-time kinematic (RTK) global positioning at a 1 to 2 cm horizontal accuracy from year to year. Each subplot consisted of the center two rows of each experimental unit by 5.3 m length and was marked by wooden stakes after planting. Soil samples, were collected between planting and the fourth leaf stage, were a composite of 14 soil cores taken to a depth of 15 cm at the 8.1 m^{-2} subplot level and w. Soil nutrient and texture analyses were conducted at Midwest Laboratories, Omaha, NE using standard laboratory procedures. Soil nutrient analysis included available P, exchangeable K, pH, soil organic matter (SOM), cation exchange capacity (CEC) (Dahnke, 1975; Kuo, 1996; Sumner and Miller, 1996; Kalra, 1997). The sodium bicarbonate method was used for P (Olsen et al., 1954) and the ammonium-acetate method was used for K (Helmke and Sparks, 1996). Available water holding capacity (AWC) was calculated using soil texture and SOM based on Saxton and Rawls (2006).

2.3. Grain yield and topographic spatial data

The plot area was mechanically combine-harvested with a calibrated Integra yield monitor (Ag Leader Technology, Ames, IA) and GPS receivers to attain site-specific maize grain yield and moisture. The harvest width was 9.1 m; where the center 12 rows of the 16-row plot were machine harvested and the second row of the plot was used for collection of ear samples. Yield monitor data were processed using SMS Basic software (Ag Leader Technology, Ames, IA) before exporting to ArcMap (ESRI, Redlands, CA). ArcMap was used to determine yield and grain moisture at the subplot level by creating

6-m buffers around the central point of the subplot followed by a spatial join of the yield information. The buffer distance was half the plot width resulting in yield information for each subplot being a mean of approximately five to seven yield monitor data points. Topographic data were generated using 0.61 m contours from the Light Detection and Ranging (LIDAR) 3-m Digital Elevation Model (DEM) of Boone and Story counties (Iowa) available from the Natural Resources Geographic Information Systems Library of the Iowa Department of Natural Resources (https://programs.iowadnr.gov/nrgislibx/). ArcMap spatial analyst tools were used to determine in-field elevation, slope, slope curvature, and slope aspect for each subplot. Positive curvature values result from convex slopes and negative curvature values result from concave slopes. Slope aspect identifies the direction a slope faces (0 to 360 degrees). For this analysis slope aspect was transformed to 'northness' with values of –1 to 1 where slope aspects of negative one are more south facing and slopes of positive one are more north facing.

2.4. Grain composition

Ear samples were collected the day of mechanical harvest from each subplot for determination of grain composition. In 2012, 14 consecutive ears per subplot were collected and in 2013 and 2014, eight consecutive ears per subplot were collected. Ear samples were shelled using an AEC small batch sheller (AEC Group, Charles City, IA). A grain subsample was analyzed for grain composition using NIRS with an Infratec 1229 whole grain analyzer (FOSS, Hillerød, Denmark) with artificial neural network models developed by the Iowa Grain Quality Initiative (Iowa State University, Ames, IA). Grain composition included protein, starch, and oil concentration. Grain density, specific gravity of kernels (g cm^{-3}), was also measured by the Infratec unit.

2.5. Statistical analysis

A mixed model procedure was used to determine independent variable effects of seeding rate, grain yield, soil attributes, and topographic characteristics on maize grain composition (SAS Institute, 2012). The location × year × seeding rate × replication interactions were considered random effects. Based on an initial combined analysis that found significant location and year main effects and location × year interactions (results not shown), the statistical procedures presented for grain composition were carried out by site-year with seeding rate × replication were assigned as random effects.

3. Results

3.1. Weather conditions

The 2012 growing season rainfall was more than 200 mm below the 30-year means of 700 mm and 704 mm at Ames and Kelley (Fig. 1) and was considered a widespread drought across Iowa. The 2013 growing season rainfall (Ames, 643 mm and Kelley, 660 mm) was near the 30-year means, however, April and May were wetter than normal creating poor conditions for planting as reflected in a late planting date of 18 June at Kelley. Rainfall in 2014 was nearly 300 mm (140 percent) above the 30-year mean for the growing but May rainfall was near normal and July was below normal. In 2012, GDD was above normal by nearly 150 GDD for the entire growing season while the 2013 and 2014 GDD was below normal at the end of the season by 25 and 90 GDD, respectively (Fig. 2). While the 2013 GDD was only slightly below normal, the months of August and September had greater than normal accumulation for the end of the grain filling period. In 2014, the July and September GDD were below normal while the rest of the growing season was near normal.

3.2. Grain composition

Grain composition generally had low coefficients of variation (CV) across sites-years with a mean CV of 5.85%, 3.48%, and 0.63% respectively for grain protein, oil, and starch concentrations (Fig. 3). The mean grain protein concentration was higher at Ames in 2013 (92.0 g kg^{-1}) than either 2014 (79.6 g kg^{-1}) or 2012 (73.7 g kg^{-1}) while grain protein was there was not a lot of variation at Kelley. At both Ames and Kelley, grain oil concentration was higher in 2013 than either 2012 or 2014. Grain starch was much lower in 2012 compared to 2013 and 2014 at both sites.

Maize grain yield influenced grain protein at both sites in 2012 (Table 1; Fig. 4). Grain protein decreased at higher grain yield levels. Grain yield had an effect on grain oil at Ames in 2012 and Kelley in 2014 where grain oil concentrations increased with increasing yield levels (Table 2). Grain starch was affected by grain yield in 2012 at both sites where higher yields resulted in higher grain starch concentrations.

Maize seeding rate as a main effect did not influence grain protein, oil, or starch concentrations in any site-year (Tables 1 – 3). Seeding rate interactions with soil attributes and topographic characteristics were also limited. The seeding rate × K interaction was significant at Ames in 2012 as was the seeding rate × aspect interaction at Ames in 2014. There were not any interactions with seeding rate for grain oil concentration. Grain starch was affected by two seeding rate interactions at Kelley in 2013 (seeding rate × pH) and 2014 (seeding rate × clay content). Soil attributes and topographic characteristics had few significant main effects or interactions with maize seeding rate (Tables 1 – 3). At both sites in 2012, grain protein decreased at higher available P levels, however, at Ames in 2014, there was a slight increase of grain protein in response to increasing available P (Fig. 5). Grain protein also increased with in-field elevation at Ames in 2013 and Kelley in 2012 (Fig. 6). Grain oil concentration increased with exchangeable K at Ames in 2014 but decreased with exchangeable K at Kelley in 2014 (Fig. 9). However, grain starch had a quadratic response to slope at Ames in 2013 and Kelley in 2012 with lower grain starch concentrations at larger slopes (Fig. 8).

4. Discussion

4.1. Weather conditions

The three years of this study provided a good opportunity to evaluate seeding rates under three unique growing season environments. In 2012, GDD was above normal the entire growing season and was combined with below normal rainfall creating drought conditions. A possible explanation is the greater demand for water use likely resulted in a depletion of plant available water by the end of vegetative development and resulted in deeper corn root growth to sustain plant transpiration. Even with heat and moisture stresses being present at the same time, there was minimal effect on corn yields. Excess rainfall in April and May of 2013 not only delayed planting at Kelley but reduced plant stand densities at Ames due to saturated or near saturated soil conditions. Early growing season rainfall combined with the below normal GDD resulted in minimal heat and moisture stress to the crop even though rainfall was below normal from mid-June through September. The 2014 crop experienced excess rainfall the entire growing season with below normal GDD from pollination (July) through maturity (September). The below normal GDD extended the grain filling period by approximately seven days

4.2. Influence of main and interaction effects on grain composition

Maize grain composition was influenced by grain yield as well as environmental conditions but not by seeding rate. Our hypothesis was that grain composition would be affected by seeding rate but our results do not support that hypothesis. Grain protein concentration was higher at lower grain yield levels in stressful environments such as 2012. Contrary to grain protein, grain starch concentration was greater at higher yield levels in stress environments. In a low- or non-stress growing season such as 2013 and 2014, neither grain protein nor starch concentration was influenced by grain yield. However, in water stress environments, diminished water uptake not only limits photosynthetic supply and translocation to the grain but also has the potential to limit N uptake. Therefore, grain protein synthesis is reduced while grain starch synthesis is maintained. This results in grain starch synthesis at the cost of grain protein synthesis (Watson et al., 2003).

Maize seeding rate interactions with soil attributes or topographic characteristics did not reliably influence grain composition. Generally the main effects of soil attributes and topographic characteristics more frequently influenced concentrations of grain protein and starch than grain oil concentration. Our results show increasing available P had a negative effect on grain protein in stress years while it had a slightly positive effect in a cool year with adequate to excess rainfall. This contrasts with the results of Genter et al. (1956) who determined that P fertilization did not affect grain protein. Our results do agree with Genter et al. (1956) and Welch (1969) that grain protein is not influenced by exchangeable K. Both Genter et al. (1956) and Welch (1969) documented slight grain oil increases from increased K fertilization in contrast to our results where exchangeable K effect on grain oil was inconsistent. A possible explanation of inconsistent grain oil response to exchangeable K is that, while there was no visual K deficiency, exchangeable K below 160 ppm could limit grain yield production. Topographic characteristics were more important for explaining variation in grain protein and starch concentrations than for explaining grain oil concentration. Grain protein concentration was positively influenced by in-field elevation while grain starch concentration was negatively affected by slopes greater than ten degrees. Our results confirm earlier reports from Minnesota and Iowa where higher in-field elevations resulted in lower grain protein concentration and that a lack of soil moisture resulted in low starch concentrations (Nugteren, 1999).

5. Conclusions

Maize grain yield explained a greater percentage of the variation in grain composition than did seeding rate, soil attributes, and topographic characteristics but even grain yield had limited usefulness in 2013 and 2014. While seeding rate is a management practice that can be easily changed within a field, it is not a practice that can be used reliability to alter grain composition. The ability to collect spatial data may prove successful for understanding soil and topographic variability but utilizing it for determining variable seeding rates to achieve grain composition goals may have limited success. Our results do not support the use of soil attributes and topographic characteristics in determining variable seeding rates to enhance grain composition characteristics.

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Table 1 Significance of seeding rate, maize grain yield, soil attributes, and topographic characteristics on grain protein at Ames and Kelley, 2012 – 2014.

	Ames			Kelley		
	2012	2013	2014	2012	2013	2014
Grain yield	*	NS	NS	***	NS	NS
SR	NS	NS	NS	NS	NS	NS
P	*	NS	**	NS	**	NS
P × SR	NS	NS	NS	NS	NS	NS
K	NS	NS	NS	NS	NS	NS
K × SR	*	NS	NS	NS	NS	NS
pH	*	NS	NS	NS	NS	NS
pH × SR	NS	NS	NS	NS	**	NS
CEC	NS	NS	NS	NS	**	NS
CEC × SR	NS	NS	NS	NS	NS	NS
SOM	NS	*	NS	NS	NS	NS
SOM × SR	NS	NS	NS	NS	NS	NS
S_a	NS	NS	NS	NS	NS	NS
S_a × SR	NS	NS	NS	NS	NS	NS
C_l	NS	NS	NS	NS	NS	NS
C_l × SR	NS	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	*
S × SR	NS	NS	NS	NS	NS	NS
C	NS	NS	*	NS	NS	NS
C × SR	NS	NS	NS	NS	NS	NS
A	NS	NS	NS	NS	NS	NS
A × SR	NS	NS	*	NS	NS	NS
E	NS	**	NS	**	NS	NS
E × SR	NS	NS	NS	NS	NS	NS
AWC	NS	NS	NS	*	NS	NS
AWC × SR	NS	NS	NS	NS	NS	NS

Note: SR, seeding rate; P, available phosphorus; K, exchangeable potassium; CEC, cation exchange capacity; SOM, soil organic matter; S_a, sand content; C_l, clay content; S, slope percentage; C, slope curvature; A, slope aspect; E, elevation; AWC, plant available water capacity; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

Table 2 Significance of seeding rate, maize grain yield, soil attributes, and topographic characteristics on grain oil at Ames and Kelley, 2012 – 2014.

	Ames			Kelley		
	2012	2013	2014	2012	2013	2014
Grain yield	*	NS	NS	NS	NS	*
SR	NS	NS	NS	NS	NS	NS
P	NS	NS	NS	NS	NS	*
P × SR	NS	NS	NS	NS	NS	NS
K	NS	NS	**	NS	NS	*
K × SR	NS	NS	NS	NS	NS	NS
pH	NS	NS	NS	NS	NS	NS
pH × SR	NS	NS	NS	NS	NS	NS
CEC	NS	NS	NS	NS	NS	NS
CEC × SR	NS	NS	NS	NS	NS	NS
SOM	NS	NS	NS	NS	NS	NS
SOM × SR	NS	NS	NS	NS	NS	NS
S_a	NS	NS	NS	NS	NS	NS
S_a × SR	NS	NS	NS	NS	NS	NS
C_l	NS	NS	NS	NS	NS	NS
C_l × SR	NS	NS	NS	NS	NS	NS
S	NS	NS	NS	NS	NS	NS
S × SR	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	NS	NS	NS
C × SR	NS	NS	NS	NS	NS	NS
A	NS	*	NS	NS	NS	NS
A × SR	NS	NS	NS	NS	NS	NS
E	NS	NS	**	NS	NS	NS
E × SR	NS	NS	NS	NS	NS	NS
AWC	NS	NS	NS	NS	NS	NS
AWC × SR	NS	NS	NS	NS	NS	NS

Note: SR, seeding rate; P, available phosphorus; K, exchangeable potassium; CEC, cation exchange capacity; SOM, soil organic matter; S_a, sand content; C_l, clay content; S, slope percentage; C, slope curvature; A, slope aspect; E, elevation; AWC, plant available water capacity; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

Table 3 Significance of seeding rate, maize grain yield, soil attributes, and topographic characteristics on grain starch at Ames and Kelley, 2012 – 2014.

	Ames			Kelley		
	2012	2013	2014	2012	2013	2014
Grain yield	*	NS	NS	***	NS	NS
SR	NS	NS	NS	NS	NS	NS
P	NS	NS	NS	NS	*	NS
P × SR	NS	NS	NS	NS	NS	NS
K	NS	NS	NS	NS	NS	NS
K × SR	NS	NS	NS	NS	NS	NS
pH	*	NS	NS	NS	NS	NS
pH × SR	NS	NS	NS	NS	*	NS
CEC	NS	NS	NS	NS	**	NS
CEC × SR	NS	NS	NS	NS	NS	NS
SOM	NS	*	NS	NS	NS	NS
SOM × SR	NS	NS	NS	NS	NS	NS
S_a	NS	NS	NS	NS	NS	NS
S_a × SR	NS	NS	NS	NS	NS	NS
C_l	NS	NS	NS	NS	NS	NS
C_l × SR	NS	NS	NS	NS	NS	*
S	NS	NS	NS	NS	*	**
S × SR	NS	NS	NS	NS	NS	NS
C	NS	NS	NS	NS	NS	NS
C × SR	NS	NS	NS	NS	NS	NS
A	NS	NS	NS	NS	NS	NS
A × SR	NS	NS	NS	NS	NS	NS
E	NS	**	NS	*	NS	NS
E × SR	NS	NS	NS	NS	NS	NS
AWC	NS	NS	NS	*	NS	NS
AWC × SR	NS	NS	NS	NS	NS	NS

Note: SR, seeding rate; P, available phosphorus; K, exchangeable potassium; CEC, cation exchange capacity; SOM, soil organic matter; S_a, sand content; C_l, clay content; S, slope percentage; C, slope curvature; A, slope aspect; E, elevation; AWC, plant available water capacity; *, significant at the 0.05 probability level; **, significant at the 0.01 probability level; ***, significant at the 0.001 probability level; NS, not significant.

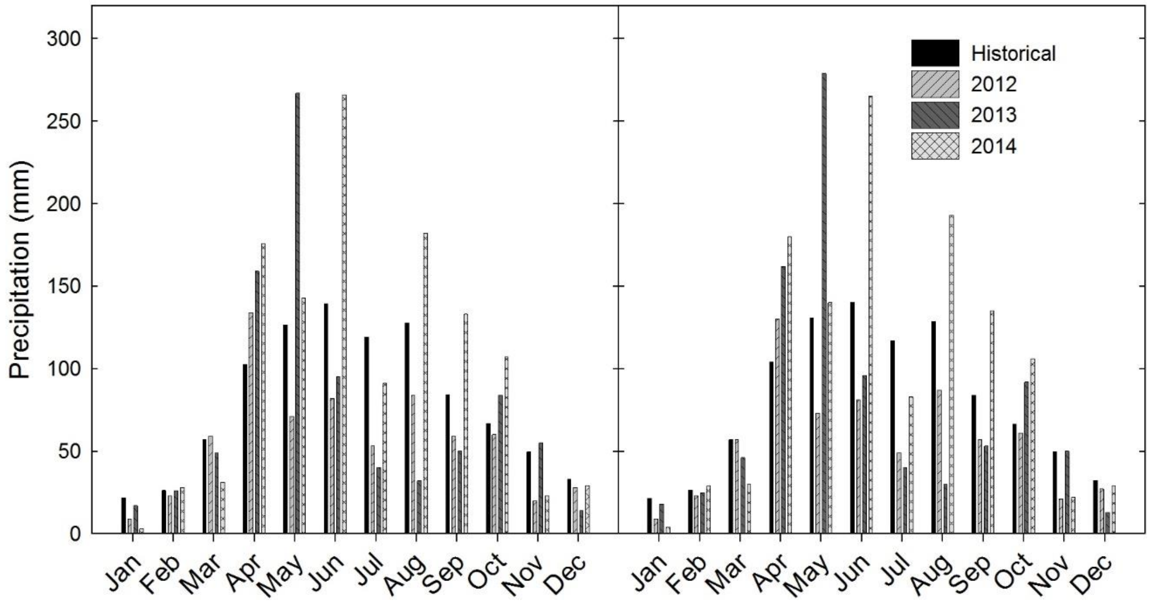

Fig. 1. Monthly and long-term precipitation at Ames and Kelly, Iowa from 2012 to 2014 and the 30-year average. Growing season totals at Ames were 483 mm, 643 mm, and 991 mm respectively for 2012, 2013, and 2014. Growing season totals at Kelley were 477 mm, 660 mm, and 996 mm respectively for 2012, 2013, and 2014.The 30-year average for both Ames and Kelley is 700 mm and 704 mm respectively. The growing season was defined as 1 April to 30 September.

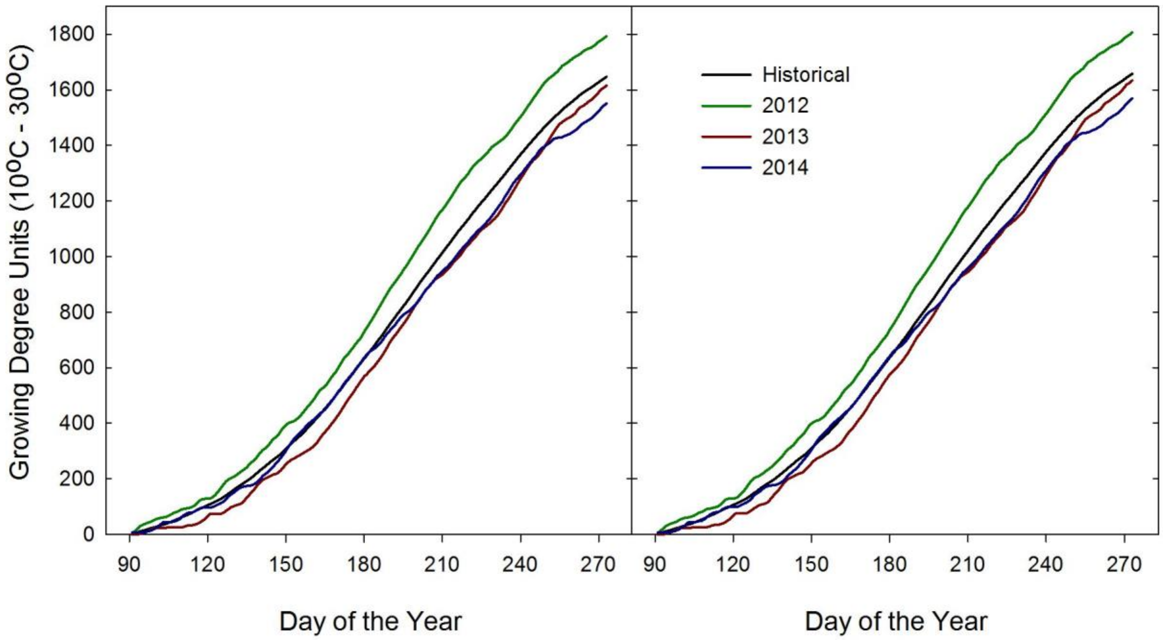

Fig. 2. Accumulated growing degree days (base 10ºC – 30ºC) at Ames and Kelly, Iowa from 2012 to 2014 and the 30-year average (black line). Growing season accumulation at Ames was 1793, 1615, and 1551 respectively for 2012 (green line), 2013 (blue line), and 2014 (red line). Growing season totals at Kelley were 1807, 1633, and 1556 respectively for 2012, 2013, and 2014. The 30-year average for both Ames and Kelley is 1647 and 1658 respectively. The growing season was defined as 1 April to 30 September.

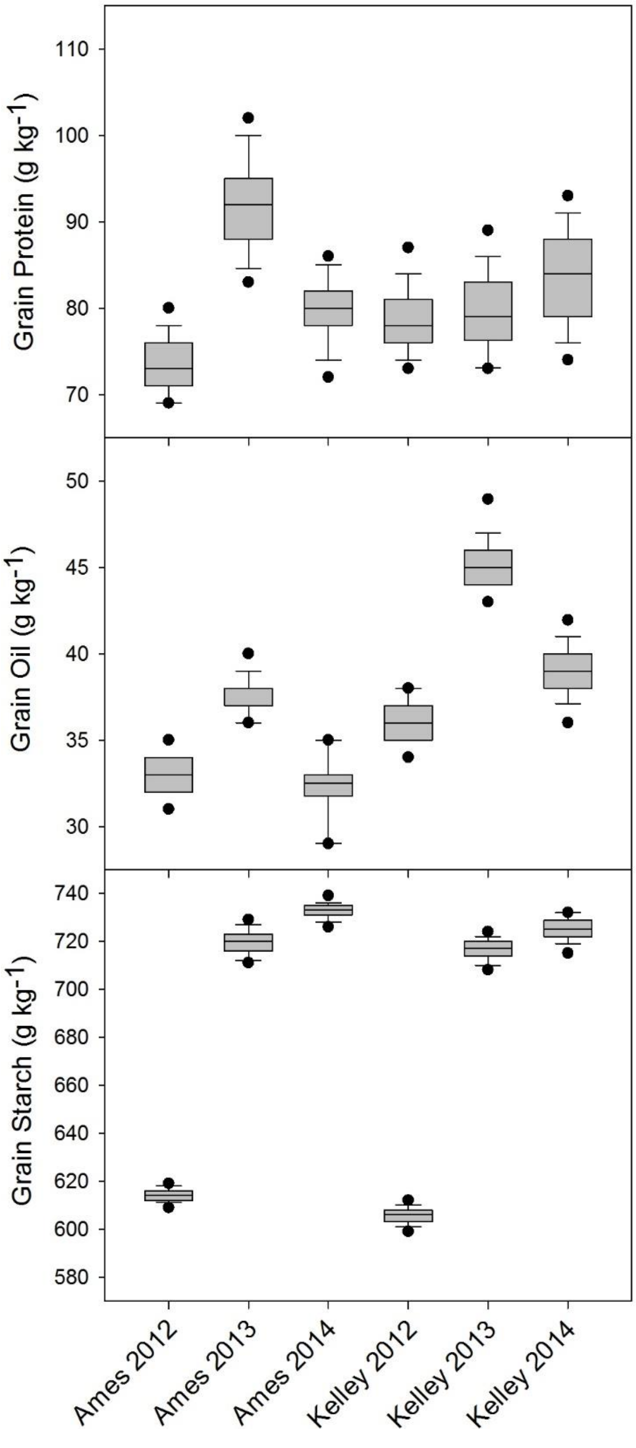

Fig. 3. Grain composition descriptive statistics for Ames and Kelley, 2012 – 2014. Median, line within the box; 25th/75th percentile, box; 10th/90th percentile, whiskers; 5th/95th percentile, black dot.

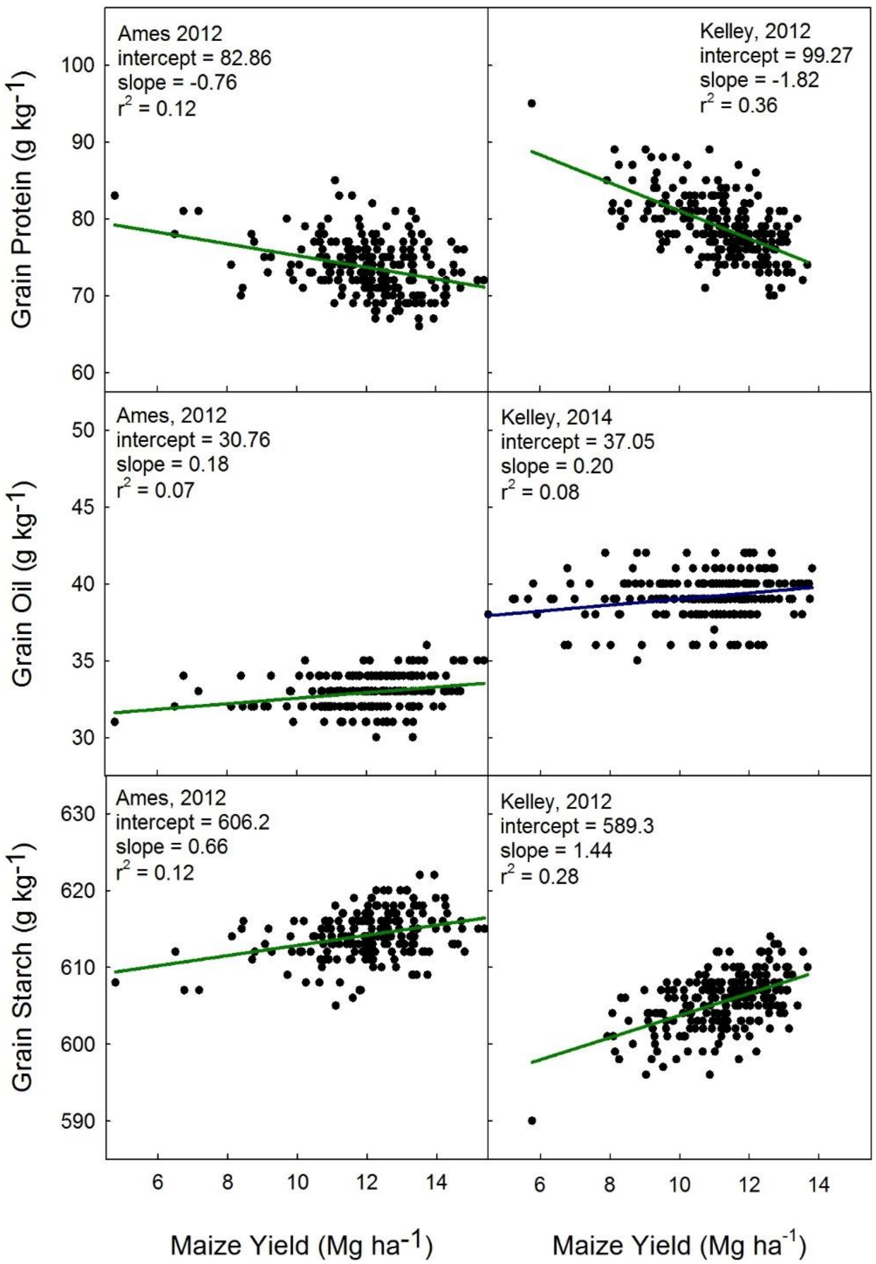

Fig. 4. Grain composition response to maize grain yield for Ames (left side) and Kelley (right side), Iowa, 2012 and 2014. There were no significant grain composition parameters in 2013.

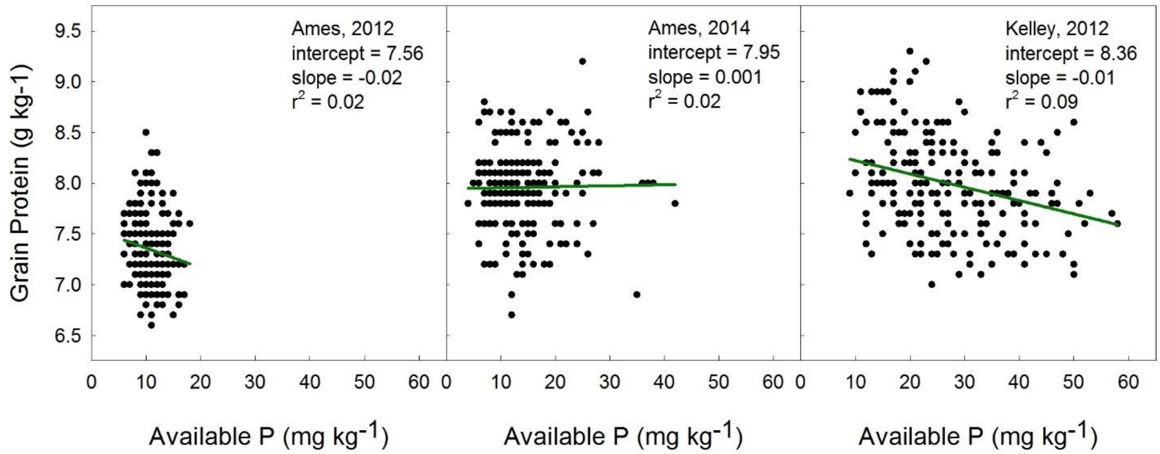

Fig 5. Grain protein concentration response to available P for Ames in 2012 (left) and 2014 (center) and Kelly in 2012 (right).

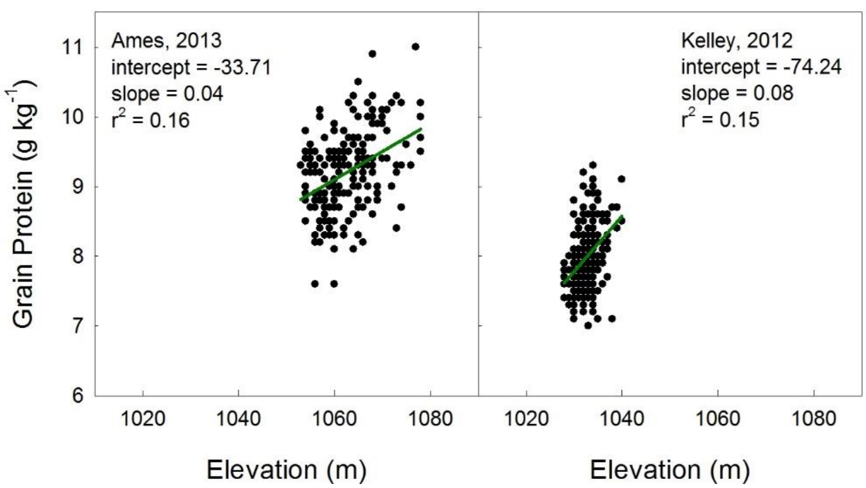

Fig 6. Grain protein concentration response to in-field elevation for Ames in 2013 (left) and Kelly in 2012 (right).

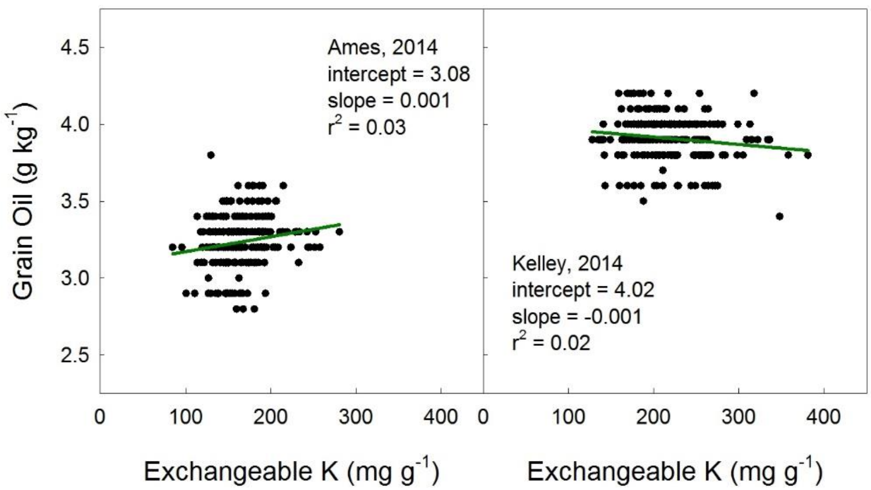

Fig 7. Grain oil concentration response to exchangeable K for Ames in 2014 (left) and Kelly in 2014 (right).

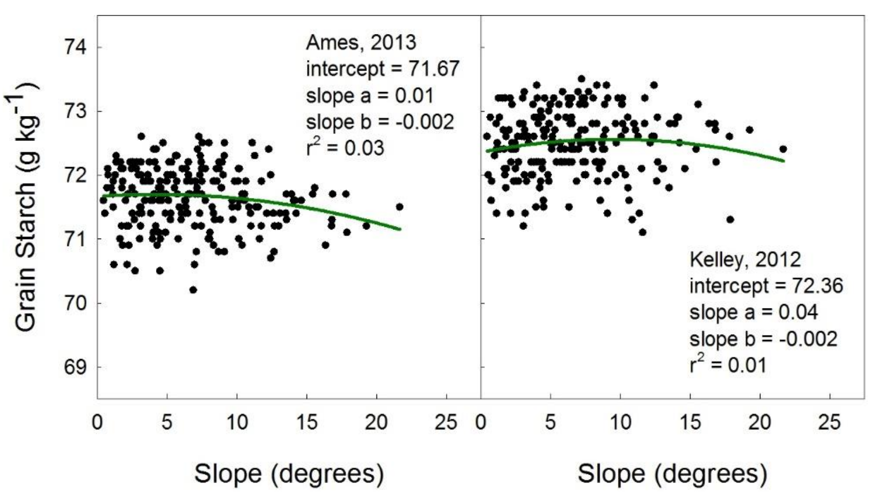

Fig 8. Grain starch concentration response to slope for Ames in 2013 (left) and Kelly in 2012 (right).

CHAPTER V

CONCLUSION

The fields used in this study proved to have substantial soil attribute and topographic characteristic variability in addition to considerable corn grain yield and optimum seeding rate variability. Individual site-years exhibited different corn yield and seeding rate responses due in part to differences in field variability. In dry conditions, such as experienced in 2012, slope, slope curvature, in-field elevation, and soil organic matter were most consistently correlated with corn grain yield. Regression models for all site-years were inconsistent in the amount of yield variability accounted for by the soil attributes and topographic characteristics (16% to 77%). When seeding rate optimization was performed, only three of nine site-years resulted in meaningful seeding rate response curves that warranted use of variable seeding rate across fields. A fourth site-year resulted in a seeding rate optimization with a range of seeding rates (92,950 to 95,430 seeds ha^{-1}) too narrow to justify variable rate seeding. There was considerable variation of attributes included in the optimization model. The optimization model utilized slope curvature, in-field elevation, and pH interactions with seeding rate to determine the slope of the optimization response curve at Ogden in 2012, 2013, and 2014 respectively.

The importance of corn seeding rate on grain yield components was evident in this research. As seeding rates increased, kernel weight, kernel rows, and kernel number ear^{-1} decreased. Additionally, increases in seeding rate resulted in a higher occurrence of zipper ears and plant barrenness, especially in 2012 when rainfall and soil moisture was limiting. The results did not show consistent evidence of seeding rate interactions with soil attributes or topographic characteristics, however, the main effects of available P and soil pH did influence kernel number row^{-1}, kernel weight, and kernel density. Additionally, there was strong evidence that in-field elevation combined with reliable rainfall forecasts can be used to determine field areas with potential for greater kernel weight and kernel density.

Maize seeding rates and seeding rate interactions with soil attributes and topographic characteristics did not reliably influence grain composition. Grain yield was more reliable in explaining grain composition but had limited usefulness in 2013 and 2014. While seeding rate is a management practice that can be changed easily within a field, it is not a practice that can be used reliability to attain desired effects on grain composition. The ability to collect spatial data can be successful for understanding soil and topographic variability but utilizing it for determining variable seeding rates to achieve grain composition goals is limited. The results of this research show little support for use of soil attributes and topographic characteristics in determining variable seeding rates to enhance grain composition characteristics.

The ability to collect spatial data can be used to understand soil, topographic, and yield variability but utilizing it for variable rate seeding applications has limited success. Determining a single optimum seeding rate methodology based on soil and/or topographic attributes across a farming operation seems unlikely due to seeding rate response and interactions with variability of climatic conditions and field characteristics. Furthermore, effects and interaction of soil and topographic attributes with seeding rates do not consistently influence corn yield components or composition. Based on this study, further research needs conducted to better understand how soil attributes, topographic characteristics, seeding rate, and their interactions can be used effectively to manage infield spatial variability.